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RESEARCH MEMORANDUM

CHARACTERISTICS OF A HYDRAULIC CONTROL DETERMINED FROM TRANSIENT DATA OBTAINED WITH A TURBOJET ENGINE AT ALTITUDE

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CHARACTERISTICS OF A HYDRAULIC CONTROL DETERMINED FROM TRANSIENT DATA OBTAINED WITH A TURBOJET ENGINE AT ALTITUDE

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SUMMARY

Characteristics of a hydraulic control were determined by analyzing transient data obtained with a turbojet engine operating in the altitude wind tunnel. The transfer function of the speed - fuel flow control was obtained from a frequency-response analysis of transient responses of the controlled engine to sudden changes in the exhaust-nozzle area. An analog computer investigation was then conducted to verify the transfer functions obtained from the frequency-response analysis. This analog investigation also indicated the existence of additional small lags which could not be detected by the frequency-response analysis. The excellent over-all performance of the speed control is attributed to the elimination of large lags in the control system, thereby permitting the use of relatively high loop gains while still maintaining satisfactory damping in transients. The temperature control circuit, which normally contributes instability, was not operating during the investigation.

The schedule of fuel flow as a function of compressor pressure rise for the surge control was obtained from the responses of these variables to throttle burst accelerations from idle to full thrust. The investigation revealed that the following two problems arise in the present surge control: First, if the schedule is set for safe altitude operation, then a considerable amount of the available acceleration is lost at sea level; second, the schedule does not provide surge protection if accelerations from engine speeds below idle, such as would occur during altitude starting, are attempted. A modification of the control which more closely matches the engine surge characteristics for a broad range of engine and flight conditions is therefore suggested.

INTRODUCTION

An investigation of a turbojet engine and that part of its control which meters engine fuel flow was conducted in the NACA Lewis altitude

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wind tunnel to determine the steady-state and transient performance of the controlled and uncontrolled engine. As a part of this program, transient operating data for the controlled engine were taken, and an analysis of the data was made to determine some of the important characteristics of the control that are not directly discernible from an examination of transient responses. The characteristics concerning which information is desired are transfer functions, schedules, and limits. Such a description furnishes information necessary for studies of system stability and transient response which are the basis of control evaluation. The results of this analysis, as well as the methods of analysis used, are presented in this report. 2777

The form of the transfer function and the values for its constants were obtained for that portion of the control which maintains the engine at full speed in a closed-loop system by conducting a frequency-response analysis of certain of the transient data. The results of this phase of the analysis are presented for transient data covering a range of altitudes from 10,000 to 45,000 feet at a nominal ram pressure ratio of 1.02.

Further studies of that portion of the control which maintains the engine at top speed in a closed-loop system were made by simulating the controlled engine on an electronic analog computer. The form and the constants of the transfer function obtained for the control by the frequency-response analysis were verified by a comparison of the results of analog computer studies with the experimental transient data. Additional studies using the simulated system were made to study the effects of high-frequency dynamic terms which may be present but which were unobtainable from the frequency-response analysis.

Information is presented to show the action of the control in preventing the engine from encountering surge while permitting rapid accelerations for three different adjustments of the control. The schedule imposed by the control is compared with engine requirements for operation at an altitude of 15,000 feet and a nominal ram pressure ratio of 1.02. The analysis is extended to examine the effect of operation at other altitudes to illustrate the manner in which the control operates, and a modification of the present control is suggested which should considerably improve its effectiveness.

EXPERIMENTAL APPARATUS

Engine. - A prototype turbojet engine with a variable-area exhaust nozzle was used in this investigation. An afterburner was attached, but was not operating during the investigation.

Control. - An hydraulic control was used to meter engine fuel flow. The control is described in a later section of this report. A separate electronic control was used to position the exhaust nozzle.

Test facilities. - A cowled engine, with its inlet open to tunnel free stream, was installed in the 20-foot-diameter test section of the Lewis altitude wind tunnel. The installation is shown in figure 1.

Instrumentation. - Engine parameters were recorded during transients on three six-channel, direct-writing oscillographs. In table I are summarized the parameters recorded, instrumentation used to measure values of the parameters in the steady state, sensing devices used to measure the variations in parameters during transients, and the frequency-response range of the transient instrumentation. A description of the transient instrumentation is given in appendix A.

DESCRIPTION OF HYDRAULIC CONTROL

During the present investigation, only that portion of the hydraulic control which varies engine fuel flow was available. The control in its complete form contains provisions for metering engine and afterburner fuel flow and positioning the exhaust nozzle. The desired result is control of thrust in response to the pilot's power lever with the maintenance of safe engine operation. Thrust is varied by scheduling engine fuel flow as a function of power lever position with the exhaust nozzle wide open for operation below full speed. After approximately full speed is reached, thrust is varied by scheduling the exhaust-nozzle area with power lever position while the engine is maintained at full speed by another portion of the control. If afterburner thrust is desired, the power lever is advanced into the afterburning range. Compressor discharge pressure is sensed by the control to provide the proper afterburner fuel flow for changes in the flight condition.

For the portion of the hydraulic control used in this investigation, regulation of engine fuel flow is accomplished by three valves placed in series, as shown in figure 2. The pressure drop across the three valves, denoted as the throttle, acceleration, and overspeed valves, is regulated by means of a differential pressure relief valve so that a given position of the three valves will result in a definite fuel flow. The action of this part of the control is best understood by considering each valve individually, since each one is of primary importance in only one region of engine operation.

During steady-state operation below top speed the overspeed valve is wide open, the acceleration valve is open sufficiently to have only a small effect, and the fuel flow is determined by the position of the throttle valve. The throttle valve is positioned in direct response to the pilot's power lever. When the power lever is at the idle position, the throttle valve is fully closed and a bypass line connected across the throttle valve supplies the idle fuel flow, which is normally adjusted to 1350 pounds per hour. With a set idle fuel flow, the idle speed of the engine increases as the altitude is increased, as shown in figure 3.

When the power lever is advanced rapidly as in a throttle burst, 2777
the throttle valve is suddenly opened. Under this condition, the fuel flow increases rapidly and the acceleration valve assumes control of the fuel flow. This valve is positioned by the acceleration valve actuator, which is designed to position the acceleration valve in response to compressor pressure rise (compressor outlet total pressure minus compressor inlet total pressure) in such a manner that compressor stall or surge will be avoided during acceleration. Two screw adjustments are included on the acceleration valve actuator to adjust the schedule of fuel flow as a function of compressor pressure rise so that satisfactory operation can be obtained. One of these adjustments varies the amount of fuel flow obtained for a given compressor pressure rise, and the other sets the minimum value of acceleration fuel flow that can be obtained at a low compressor pressure rise.

As the engine approaches full speed, the overspeed valve begins to close to maintain the engine at full speed. Under the condition of full speed, the overspeed valve, the overspeed relay, and the engine form a closed-loop control system which will be called the speed control. The overspeed relay consists of a flyball governor and a hydraulic servo for positioning the overspeed valve in response to the flyball governor. The function of the speed control is to provide satisfactory control of engine speed during steady-state and transient operation at full speed.

The exhaust nozzle was positioned by a separate electronic control during the experimental investigation. In the complete control system, exhaust-nozzle area is to be scheduled as a function of power lever position, with provisions for trimming this schedule by either a manual or an automatic temperature trim. There is, however, a speed switch in the overspeed valve assembly which will not allow the exhaust nozzle to close until the engine speed has reached approximately 95 to 98 percent of full speed. This speed switch is included to prevent the exhaust nozzle from closing during accelerations until nearly full speed is obtained. For afterburner operation a pressure-operated switch activates a circuit which opens the exhaust nozzle upon the initiation of afterburning and closes the nozzle should afterburner blow-out occur.

EXPERIMENTAL PROCEDURE

Transient data were obtained for the controlled engine during the altitude wind tunnel investigation by subjecting the engine to two types of disturbance. In both cases, engine parameters were measured continuously on oscillograph recorders. Calibration of the oscillograph traces was accomplished by taking readings of the steady-state instruments before and after each transient.

One type of disturbance consisted in subjecting the controlled engine to a sudden change in the exhaust-nozzle area while the engine was operating at full speed with the throttle valve wide open. The responses to this type of disturbance therefore provide information on the action of the speed control and its ability to perform its prescribed functions. This part of the investigation was performed for a range of altitudes from 10,000 to 50,000 feet at a nominal ram pressure ratio of 1.02 and included exhaust-nozzle disturbances of various sizes and in both directions. A typical transient response of the controlled engine to this type of disturbance is presented in figure 4.

The other type of disturbance consisted of throttle burst accelerations from low speed (exhaust nozzle open) to full thrust (exhaust nozzle almost closed). These accelerations were made by rapidly advancing the power lever and allowing the engine to accelerate with the exhaust nozzle open until engine speed reached from 95 to 98 percent of full speed. At this time the exhaust nozzle was closed to the full thrust position by manually operating the electronic control used for positioning the exhaust nozzle. This action effectively simulated a throttle burst from low power to full thrust with the complete control, and the transient responses of the engine to this disturbance illustrate the effectiveness of the control in rapidly accelerating the engine while preventing compressor surge.

First setting. - Data for the throttle burst accelerations were obtained for three different adjustments of the acceleration valve actuator. The first of these settings was made by the manufacturer at sea-level static conditions.

With the manufacturer's setting no surge was encountered at any altitude during accelerations from the control idle fuel flow. In order to determine the effect of operation closer to the surge region, investigations were conducted with two other adjustments of the acceleration control.

Second setting. - For the second setting the acceleration minimum fuel flow screw adjustment was turned 1/4 turn in from the first setting to increase the acceleration minimum fuel flow at low speeds, and the acceleration fuel flow screw adjustment was turned 1/8 turn out to increase the scheduled fuel flow for any given value of compressor pressure rise at higher speeds.

Third setting. - For the third setting the acceleration minimum fuel flow screw adjustment was turned 1/8 turn farther in. The effect of these settings on the scheduled fuel flow will be illustrated later.

The throttle burst accelerations were made over a range of altitudes from 5000 to 20,000 feet at a nominal ram pressure ratio of 1.02. The response of the controlled engine during a typical throttle burst accel- 2777
eration is shown in figure 5.

Unless otherwise specified, all the data presented herein were either taken at or adjusted to the standard temperature for the given flight condition.

FREQUENCY-RESPONSE ANALYSIS FOR DETERMINATION OF SPEED CONTROL TRANSFER FUNCTION

Determination of the transfer function of any linear physical system can be accomplished by appropriate analysis of transient responses of that system to some arbitrary disturbance. The transfer function and time response of a linear system are related by the Laplace transform, which can therefore be used to obtain the transfer function if the time response is known. In the case of the speed control portion of the control, the transient data obtained for the controlled engine when subjected to a sudden change in the exhaust-nozzle area while operating at full speed provide the necessary data for such an analysis.

Theory of Frequency-Response Analysis

If the speed control is assumed to be a linear system for the disturbances encountered, its transfer function can be expressed as the ratio of the Laplace transform of the output function to that of the input function for any given disturbance

$$F(p) = \frac{L\left\{f_o(t)\right\}}{L\left\{f_i(t)\right\}}$$

(Symbols are defined in appendix B.)

as shown in reference 1. Furthermore, for a system initially at rest,

$$L\left\{f'(t)\right\} = p\ L\left\{f(t)\right\}$$

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so that

$$\frac{L\left\{f_o'(t)\right\}}{L\left\{f_i'(t)\right\}} = \frac{p\ L\left\{f_o(t)\right\}}{p\ L\left\{f_i(t)\right\}}$$

and the transfer function can be expressed as

$$F(p) = \frac{L\left\{f_o'(t)\right\}}{L\left\{f_i'(t)\right\}}$$

This form of the equation permits easier evaluation of the transfer function because it does not require that the time functions return to the initial value, but only that they reach a steady value.

The transfer function can now be written

$$F(p) = \frac{\int_0^\infty e^{-pt}\ f_o'(t)dt}{\int_0^\infty e^{-pt}\ f_i'(t)dt}$$

and the frequency-response function is then obtained by formally replacing p by $i\omega$, so that

$$F(i\omega) = \frac{\int_0^\infty e^{-i\omega t}\ f_o'(t)dt}{\int_0^\infty e^{-i\omega t}\ f_i'(t)dt}$$

Expansion of this equation into a form applicable to the digital computing facilities available is developed in reference 2 and gives

$$F(i\omega) = \frac{f_o(T)-f_o(0)+\omega\int_0^T \left[f_o(T)-f_o(t)\right]\ \sin \omega t\ dt + i\omega\int_0^T \left[f_o(T)-f_o(t)\right]\ \cos \omega t\ dt}{f_i(T)-f_i(0)+\omega\int_0^T \left[f_i(T)-f_i(t)\right]\ \sin \omega t\ dt + i\omega\int_0^T \left[f_i(T)-f_i(t)\right]\ \cos \omega t\ dt}$$

where T is the time required for the functions to reach a stable condition and ω is any frequency desired. The integrals appearing in the expression are evaluated by a numerical integration scheme, also developed in reference 2, using digital computing machines. The computation procedure used required that the data be in the form of 121 evenly spaced readings of the time functions.

Procedure for Frequency-Response Analysis of Speed Control

For the speed control, the input is speed error while the output is fuel flow. To obtain the necessary data for the frequency-response analysis, the speed and fuel flow traces were divided into 120 equal intervals covering the time period required for the engine to complete the transient and return to a stable operating condition. Readings of engine fuel flow and the deviation of engine speed from full speed were taken at each point. These data were then used in the computing procedure to determine the frequency response of the speed control over a range of frequencies.

Results of Analysis

The results of the frequency-response analysis for two typical transients are presented in figures 6 and 7. Figure 6 is the result of analyzing the transient response shown in figure 4, which is for an altitude of 15,000 feet and a ram pressure ratio of 1.02. Figure 7 represents the frequency-response obtained by analysis of similar responses obtained at an altitude of 35,000 feet and a ram pressure ratio of 1.02. For these frequency responses (and all others obtained), asymptotes were first drawn to the data points to determine the form and evaluate the constants of the transfer function of the speed control. Using the transfer function derived in this manner, a theoretical curve was then plotted to determine whether the form and constants found with the aid of asymptotes were sufficiently accurate.

The results of analyzing a number of transient responses show that the speed control is of the proportional-plus-integral form. The values of the integral time constant and the fuel flow to speed error gain of the speed control are plotted as functions of fuel flow in figures 8 and 9, respectively. Inspection of these figures reveals that the integral time constant has a constant value of 4 seconds while the gain varies with fuel flow and therefore with the flight condition.

The frequency-response data beyond approximately 3 radians per second show considerable scatter and are not considered reliable. Excessive noise on the transient fuel flow traces, random disturbances in the experimental data, and inaccuracies in reading the transient data are probably responsible for this difficulty. Attempts to extend the useful range of the frequency-response information by smoothing the data or using a greater number of intervals failed to result in any consistent improvement.

ANALOG COMPUTER STUDIES OF SPEED CONTROL

The results of the frequency-response analysis provide satisfactory information as to the basic form and constants of the speed control. As previously noted, however, information beyond a frequency of three radians per second could not be obtained. Also, it was desirable to provide some means of verifying the results of the frequency-response analysis. This was accomplished by simulating the engine and speed control on an electronic analog computer, which also served as a means for further studies of the speed control.

Verification of Speed Control Transfer Function

Figure 10 shows the method of simulation used for the purpose of verifying the results of the frequency-response analysis. The engine was represented as a simple lag, since there was no information available to indicate the presence of any additional dynamic terms. The values of the speed to fuel flow gain and time constant of the engine at full speed were determined from data obtained with the uncontrolled engine by methods similar to those presented in reference 3. The variation of these characteristics with altitude at a ram pressure ratio of 1.02 is presented in figures 11 and 12. These characteristics were determined only with the open afterburner nozzle. The data for this exhaust-nozzle area were sufficient for the analog computer studies inasmuch as reference 3 shows the time constant to be independent of the exhaust-nozzle area, and the speed to fuel flow gain is only slightly affected by it. Furthermore, only the sudden exhaust-nozzle changes from fully closed to fully open were simulated. For this disturbance, the engine operates with the exhaust nozzle open during the greatest portion of the transient. The gain of the speed control was replotted against altitude, as shown by figure 13, to provide this information in the same form as the engine characteristics.

The results of this portion of the analog computer studies are shown and compared with experimental data in figures 14 and 15, which are for altitudes of 15,000 and 35,000 feet, respectively, at a ram pressure ratio of 1.02. The experimental data shown in figure 14 were translated from figure 4. Both these figures show a close agreement between the experimental responses and those obtained with the analog computer. Some of the deviations between the experimental data and the analog computer results are due to inaccuracies in both engine and control data along with errors in reading experimental and analog results as well as to the approximations used in simulating the system. The major portion of this deviation, however, is probably due to additional dynamic terms in the control which are undoubtedly present but which could not be determined from the frequency-response analysis.

An interesting point in regard to the engine and control data which adds additional confirmation to the results of the frequency-response analysis of the speed control is the relation between the loop gain of this control system and the maximum deviation of engine speed from full speed during the transient response to a sudden change in the exhaust- 2777
nozzle area. The variation of these characteristics with altitude is shown in figure 16. All the data for the maximum deviation from full speed were taken from the responses to a sudden change in the exhaust-nozzle area from fully closed to fully open. The loop gain was found by multiplying the fuel flow to speed error gain of the control (fig. 13) by the engine gain (fig. 11) at each altitude. An examination of figure 16 reveals that the characteristics shown are approximately mirror images of each other, which serves to confirm the relation between loop gain and altitude. The integral term will, of course, have some effect on the maximum deviation from full speed; but, in the case of the speed control, the integral time constant is large enough to make only a small difference in this characteristic.

Figure 16 also indicates the effectiveness of the speed control. The maximum deviation for a full exhaust-nozzle area change was less than 1.5 percent of full speed for all altitudes. Furthermore, data show that none of the responses was of an oscillatory nature. It can be concluded that the closed loop speed control performed very well, both in steady state and in transient. The good performance of this part of the control is the result of the relatively high loop gain used. A high loop gain was possible because the lags other than that of the engine were very small in comparison with the engine lag. A further advantage was obtained by increasing the loop gain at high altitude. Approximately the same damping was maintained because the engine time constant also increased.

Study of Effect of Additional Dynamic Terms

In order to obtain an estimate of the additional dynamic terms that might be present in the speed control and their possible magnitudes, additional dynamic terms were introduced into the simulated control. Figure 17 shows the terms used. The magnitudes of the time constants were gradually increased until the speed and fuel flow responses on the computer were definitely different from the experimental responses. This procedure was used for the simulation at an altitude of 15,000 feet, and the results of this study are presented in figures 18 and 19.

The first term introduced was a simple lag, and the speed and fuel flow responses to the same area disturbance as that shown in figure 14 are shown for the lag having time constants of 0, 0.1, 0.2, and 0.3 second in figures 18(a), 18(b), 18(c), and 18(d), respectively. The excessive amount of overshoot on the speed trace for the 0.3 second time constant indicates that this lag is definitely too large. The overshoot present on the speed trace for the 0.2 second time constant also seems rather large, but such action on the experimental responses could have been masked by noise or random disturbances. The results indicate that the first additional lag is probably not much greater than 0.1 second.

The next step was to add a second lag to the simulated control. The time constant of one lag was set to a value of 0.1 second, while the time constant of the second lag was gradually increased. The speed and fuel flow responses, again for the same area disturbance as that shown in figure 14, for the second lag with time constants of 0, 0.03, 0.05, and 0.1 second are shown in figures 18(e), 18(f), 18(g), and 18(h), respectively. Inspection of these figures reveals that a time constant of 0.1 second for the second lag is definitely too large and a value of 0.05 second appears rather large.

The responses indicate that the first additional lag is probably not much greater than 0.1 second and the second lag not much greater than 0.03 second. A comparison of the computer responses for the system with two lags of 0.1 and 0.03 second with the experimental responses for the same flight conditions is shown in figure 19. The computer responses for the system without lag are also shown. This figure indicates that the computer responses with the lags having time constants of 0.1 and 0.03 second included are closer to the experimental responses than the computer responses without the lags.

The situation for an altitude of 35,000 feet is somewhat different. Since the basic engine lag at 35,000 feet is approximately twice as large as at 15,000 feet, the system response is much less sensitive to additional small lags. Figure 15 shows, however, that the computer responses for 35,000 feet without any additional lags are already in good agreement with the experimental data. Because the system at 35,000 feet is much less sensitive to these lags, the computer responses with the two lags will also be very close to the experimental responses. On the basis of the effect of these lags on the responses at both 15,000 and 35,000 feet, it can be concluded that additional lags of this order of magnitude are very likely present in the actual system.

The elimination of large lags in the control system allows the use of a relatively high loop gain while maintaining satisfactory damping during transients. As a result, the over-all performance of the speed control was excellent. The maximum deviation of engine speed during exhaust-nozzle changes from open to closed positions was less than

1.5 percent of full speed for a broad range of altitudes. Furthermore, satisfactory transient responses were obtained for these area disturbances and for accelerations from idle to full thrust.

ANALYSIS OF ACCELERATION CONTROL

As was previously noted, the hydraulic control was designed to prevent the engine from encountering compressor stall or surge during accelerations by scheduling fuel flow as a function of compressor pressure rise. The schedules for the three settings used during the NACA investigation were obtained from an analysis of throttle burst accelerations, such as those shown in figure 5. Values of fuel flow and compressor pressure rise at various instants of time were read from the transient traces over the period when the throttle valve is wide open and the overspeed valve has not begun to close. A plot of this data furnishes the required schedule.

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Schedule Imposed by Acceleration Control

The schedules imposed by the acceleration control for the three control settings are shown separately in figures 20(a), 20(b), and 20(c). The data for each setting were plotted separately to avoid confusion from the scatter of the data points. The schedule was drawn through the data points for each setting, and all three schedules are compared in figure 21. A steady-state operating line is included in figure 21 to illustrate the margin between the steady-state operating line and the limit imposed by the control. The flat spot on the lower portion of the schedule, called the acceleration minimum fuel flow, should have been successively higher for the second and third settings of the control. The fuel flow at this flat spot on the various traces appeared to be erratic, although the flat spot always occurred at a fuel flow near 2500 pounds per hour. Values above and below this one were found for all three settings. Above the flat spot, this portion of the schedule, denoted as the acceleration fuel flow, was higher for the second and third settings, as it should have been. This portion of the schedule should have been identical, however, for the second and third settings, since the acceleration fuel flow adjustment was the same for both settings. The small difference between these two lines may be primarily due to inaccuracies in reading the transient traces.

Effect of Setting on Acceleration

The effect of the setting on the acceleration of the engine is illustrated by figure 22, which presents the time required for the controlled engine to accelerate from idle to full speed as a function of altitude. Since the idle speed varies with altitude, its variation is shown also. Figure 22 shows that the engine accelerated faster with the second and third settings of the control. This is to be expected because a greater margin exists between the steady-state line and the limit imposed by the control schedule for the second and third settings. The difference in acceleration time is much greater at low altitudes because of the greater speed range which must be traversed. This effect also accounts for the decrease in acceleration time with altitude.

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Comparison of Control Action with Engine Requirements

For a better understanding of the action and effectiveness of the surge control, it is helpful to compare the surge line of the engine with the path followed by the engine during a throttle burst acceleration. There was, however, very little surge information available for the engine equipped with the afterburner and the afterburner exhaust nozzle. A detailed investigation of the stall and surge characteristics of this engine without an afterburner and using a smaller exhaust nozzle was made, and the results of this investigation are presented in reference 4. Data presented in reference 4 indicate that the exhaust-nozzle area does not influence the stall or surge characteristics if these are defined by compressor parameters. If these characteristics are defined by other engine parameters such as fuel flow, then the exhaust-nozzle area has a considerable effect. As shown in reference 4, the engine first encounters a high-frequency pulsation, believed to be stall, at low engine speeds and surge at the higher engine speeds. For purposes of simplicity, the combined stall and surge line, referred to as the "limit line" in reference 4, will be designated the surge line in this report. With the aid of the characteristics presented in reference 4, the data available for the engine configuration used in the controls investigation are sufficient to illustrate the general trend of the surge characteristics.

Figure 23 shows the surge line on a plot of compressor pressure ratio against generalized speed obtained for the nonafterburning engine. The surge points found for the engine with afterburner are also shown and fall on the surge line taken from reference 4, as expected. Also shown on this figure are the steady-state operating line for an altitude of 15,000 feet with the open afterburner nozzle and the path of the engine during the throttle burst acceleration of figure 5, also at an altitude of 15,000 feet. Although the engine appears to enter the surge region during the acceleration, the engine did not surge. Inaccuracies due to data scatter in this region were responsible for this error. This figure indicates that the control accelerates the engine very close to the surge line at this flight condition. It will be shown later that a small margin was available between the acceleration path followed by the control and the surge line, even though such a margin is not indicated by this figure. The effect of altitude will also be discussed later.

The relation between the surge line and the acceleration path of the controlled engine is shown also by plotting these characteristics as functions of other engine parameters. From such plots it may be possible to ascertain better surge control parameters or to evaluate more clearly the quality of the surge control examined. Such information is presented in figures 24, 25, and 26 for an altitude of 15,000 feet and a ram pressure ratio of 1.02 for the first setting of the control.

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The surge line and the control limit line are presented on a plot of fuel flow against compressor pressure rise in figure 24. Figure 25 shows the surge line along with a throttle burst acceleration on a plot of fuel flow against engine speed. In figure 26, an acceleration path and a few surge points are given on a plot of temperature against engine speed. The acceleration paths for figures 23 to 26 were obtained from the same throttle burst acceleration.

Examination of figures 24 to 26 again illustrates that the surge control allows accelerations close to the surge line for the given flight conditions. All the surge points lie above the acceleration path in these figures. These data are therefore consistent with the absence of surge during the transient shown. In addition, there is a greater margin between the steady-state, acceleration, and surge lines as defined by these parameters than there was on the plot of compressor pressure ratio against generalized engine speed. In the case of the compressor pressure ratio - generalized engine speed plot, not only is the margin between the surge and steady-state lines small, but also the variation in pressure ratio at constant speed near the surge line is extremely small. Therefore, in the region where an evaluation is most critical, this type of plot is least helpful. As a result, figures 24 to 26 permit a better evaluation of the surge control.

Effect of Altitude on Acceleration Control

Since little information on surge was available for the engine with the afterburner attached at altitudes other than 15,000 feet, generalization factors were used to obtain an indication of the fuel flow and compressor pressure rise at the surge line for other altitudes. To determine the degree of accuracy attainable by generalization, experimental and generalized surge data for the nonafterburning exhaust nozzle were compared. This comparison is shown in figure 27. The actual surge lines are shown as drawn through the data obtained from reference 4. The surge line for 35,000 feet obtained by generalizing the data for 15,000 feet compares very well with the actual experimental surge line for 35,000 feet. The surge lines at 15,000 and 35,000 feet are for a 1.02 ram pressure ratio.

Also shown are the surge lines obtained by generalizing the data for 15,000 and 35,000 feet to static sea-level conditons. Although the agreement is not good over the complete range, the results indicate that an approximate surge line for static sea-level conditions can be obtained. Data obtained at 15,000 feet while the engine was operating
2777 with the afterburner tail section and exhaust nozzle were therefore generalized to locate the approximate positions of surge lines at sea level and at 35,000 feet. The positions of these surge lines with respect to the control acceleration fuel flow line are shown in figure 28. Steady-state lines for sea-level, 15,000 feet, and 35,000 feet are shown along with the control idle fuel flow.

Examination of figure 28 shows that the surge line falls considerably below the control acceleration fuel flow line for an altitude of 35,000 feet. If, however, the idle fuel flow is considered, it can be seen that this feature of the control prevents operation in the range where the surge line is below the acceleration control limit. For an altitude of 35,000 feet, the engine is, in fact, at full speed (as was shown by fig. 3), so that accelerations will not occur at this altitude. If, however, accelerations from fuel flows below the normal idle were required, as in the case of altitude starting, careful manipulation of the throttle would be required since the control could not effectively prevent surge.

This figure further reveals that for static sea-level conditions the acceleration provided by the control line is extremely small in comparison with that available, especially at the lower end.

A study of the available surge information has indicated a method of more fully utilizing the engine acceleration capabilities. Furthermore, the proposed method provides more complete protection at high altitudes and low engine speeds. The relation of the proposed control acceleration fuel flow to the engine surge lines is presented in figure 29. It appears that a schedule in which fuel flow is directly proportional to compressor pressure rise and located as shown would be suitable for part of the control line. This part is essentially as provided at present except for a change in slope. The second part would be a modification to make the acceleration minimum fuel flow a function of compressor inlet total pressure. For example, at static sea-level conditions, the acceleration minimum fuel flow would be approximately 5500 pounds per hour, as indicated by the dashed line just below the corresponding surge line. At 15,000 feet this minimum acceleration fuel flow would drop to approximately 3000 pounds per hour, and at lower inlet pressures it would decrease accordingly. The indicated acceleration minimum fuel flows are plotted as a function of compressor inlet total pressure in figure 30. The relation is very nearly a straight line, indicating that a proportional variation of the minimum acceleration fuel flow with compressor inlet total pressure would be suitable.

A study of the effect of ambient temperature variations on the surge line was made, again using generalization factors. At static sea-level conditions, a 1 percent change in fuel flow is required for every 10° F change in temperature. To provide safe operation for a temperature of 0° F at static sea-level conditions would require a slightly lower acceleration fuel flow than that indicated by figure 29. This same proposed schedule could be used, however. Figure 31 illustrates the position of the proposed control schedule in relation to the present schedule. 2777

CONCLUDING REMARKS

The most important results obtained are summarized in three groups as follows:

Frequency-Response Analysis of Speed Control

1. The results of the frequency-response analysis were very consistent up to 3 radians per second and showed that the speed control is of the proportional-plus-integral type.

2. The integral time constant of the speed control is 4.0 seconds and does not vary appreciably with fuel flow or altitude.

3. Fuel flow to speed error gain of the speed control varies with fuel flow and therefore with altitude and Mach number for a given engine speed.

4. As a result of inconsistencies in the data beyond a frequency of 3 radians per second, the existence or nonexistence of additional high-frequency dynamic effects could not be definitely established from frequency analysis alone.

Simulation of Speed Control

1. Close agreement was obtained between experimental and simulated transients, verifying that the proportional-plus-integral form with the constants obtained provided a fairly accurate description of the control.

2. The study of high-frequency characteristics not obtainable from the frequency analysis indicated that additional dynamic terms are probably small lags.

3. The avoidance of large lags permitted the use of a high loop gain which resulted in a very effective speed control.

Acceleration Control

1. The study of altitude effects showed that the acceleration-surge control depended upon a fixed idle fuel flow for proper operation. When accelerating from engine speeds corresponding to fuel flows less than the normal fixed idle value, such as during altitude starting, pilot throttle manipulation would be necessary to avoid surge.

2. The study also indicated that the present control would utilize only a part of the available acceleration at sea level if set to operate safely for a range of altitudes.

3. A modification of the present control schedule which follows the actual surge characteristics more closely for a broader range of engine and flight conditions is proposed.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio

APPENDIX A

DESCRIPTION OF TRANSIENT INSTRUMENTATION

Recording equipment. - Engine parameters were recorded during transients on six-channel, direct-inking, magnetic-penmotor oscillographs. Each channel of the recorders was driven by either a strain analyzer or d-c type of amplifier, depending on the parameter being measured. Strain analyzer amplifiers were used with the sensing devices for pressures, fuel flow, and thrust; while d-c amplifiers were 2777
used with the sensing devices for speed, acceleration, temperature, and position. The frequency response of the penmotors in combination with either type of amplifier is essentially flat over the range from 0 to 100 cycles per second. The oscillograph chart speed was 12.5 millimeters ($2\frac{1}{2}$ units) per second.

Timing marks were introduced on certain channels by removing the signals from these channels, before or after a transient, simultaneously by means of a switch. These marks serve as a means of alining the traces from different recorders and for detecting slight variations in the lengths of individual pens.

Position indication. - The positions of the exhaust nozzle and power lever were indicated by a potentiometer attached in such a manner that the movable arm of the potentiometer was an indication of the position of the device. A d-c voltage was applied across the potentiometer so that a d-c voltage indicative of position appeared between the movable arm and either end of the potentiometer. For the transient indication, the initial level of the signal was cancelled by series addition of an adjustable voltage opposite in polarity to that of the signal. This is done since it is desired to record only the change during the transient. The signal is then applied to a d-c amplifier feeding one channel of a recorder.

The frequency response of this circuit is limited by that of the amplifier and recorder.

Turbine inlet temperature. - Turbine inlet temperature was measured by a number of sonic-type, shielded thermocouples placed at the turbine inlet and electrically connected in series. A switching arrangement was provided to bypass any of the thermocouples should they burn out or become grounded. The initial level of the signal was cancelled, and the signal was then applied to a d-c amplifier feeding one channel of a recorder.

The frequency response of this circuit is determined by the time constant of the thermocouples, which depends upon the thermocouple material, wire size used, type of junction, and mass flow conditions at the point of measurement. The thermocouple used had a time constant of approximately 0.6 second at sea-level mass flow conditions, resulting in a frequency response which is essentially flat from 0 to 0.27 cycle per second at this condition. Methods for determining the time constant of thermocouples are given in reference 6.

These same thermocouples were used for the steady-state indication. Relays were used to switch the thermocouples from the steady-state equipment to the transient equipment. Under some conditions of excessive engine vibration, chatter of relay contacts caused this temperature recording to be extremely noisy. These traces are questionable, but can be easily identified by the large amount of high-frequency noise present on the trace.

<u>Turbine discharge temperature</u>. - Turbine discharge temperature was measured by a number of 18 gage, chromel-alumel, butt-welded thermocouples placed at the turbine discharge and electrically connected in parallel. The signal from the thermocouples was applied to a magnetic amplifier to increase the amplitude of the signal without the introduction of excessive noise or drift. The magnetic amplifier was followed by an adjustable voltage to cancel out the initial level, a thermocouple compensator, and a d-c amplifier feeding one channel of a recorder.

The thermocouple compensator is an electric network which, when properly adjusted, compensates for the thermal lag of the thermocouples. A detailed discussion of the basic principles and circuitry involved is given in reference 5. This device allows the use of heavier thermocouple wire while obtaining faster response than could be ordinarily obtained with smaller wire.

The compensator was set by placing only one thermocouple in the circuit and then suddenly plunging the thermocouple from a cooled shield into the hot gas stream, effectively subjecting the thermocouple to a step change in temperature. The compensator was then adjusted until the temperature trace recorded as nearly a step as possible.

The frequency response of this circuit with the compensator properly adjusted is flat over the range from 0 to 5 cycles per second at sea-level mass flow conditions.

<u>Engine speed</u>. - An alternator on the engine provides an a-c voltage with a frequency directly proportional to speed and varying from 300 to 800 cycles per second over the speed range normally encountered. This signal was used in connection with an electronic tachometer which was modified to give an accurate steady-state and suitable transient indication of engine speed.

The steady-state indication is provided by a counting circuit which counts the input frequency for a period of 1.2 seconds, which is accurately set by a crystal controlled oscillator. This count is then presented on a neon lamp display panel for a suitable length of time after which the process is repeated. Although the count is very accurate, unless the frequency is high in relation to speed, the speed cannot be precisely defined. Consequently, the alternator signal was first applied to two stages of full-wave rectification which increased the frequency by a factor of 4. With this modification, the steady-state speed indication was precise to within 1 rpm. 2777

The transient signal was obtained by modifying an existing meter circuit included in the instrument to provide a continuous indication of frequency and, hence, speed. A d-c voltage, proportional to speed, is produced by the modified meter circuit. After cancellation of the initial level, this signal was applied to a d-c amplifier feeding one channel of a recorder.

The frequency response of this circuit is limited by a filter circuit required in the modified meter circuit and is essentially flat over the range from 0 to 10 cycles per second.

Engine acceleration. - The transient acceleration signal was obtained by differentiating the speed signal with a simple RC circuit. The signal from the differentiating circuit was applied to a d-c amplifier feeding one channel of a recorder. There is an inherent lag associated with the RC differentiating circuit which limits the frequency response to 2 cycles per second.

Air pressures. - Transient measurements of ram pressure, dynamic pressure at the engine inlet, compressor discharge pressure, turbine discharge pressure, and compressor pressure rise were made using standard four-element, strain-gage pressure pickups and strain-analyzer-type amplifiers. A network in the analyzer provides a means of adjusting the initial output of the amplifier so that only the change need be recorded.

The pressure pickups were mounted in a centrally located box designed to reduce the effect of engine vibration on the pickups.

The dynamic response of these circuits is a function of the diameter and the length of the tubing used to transmit the pressure from the engine to the pressure pickup and the density of the air. Design of tubing size is outlined in reference 7. All tubing was experimentally tested and adjusted before installation to give a frequency response which is essentially flat from 0 to 10 cycles per second at sea-level conditions.

Fuel flow. - The transient indication of fuel flow was obtained by measuring the pressure drop across an orifice in the fuel line by means of a differential strain-gage pressure pickup. The operation of the pressure pickup is the same in this case as for those used to measure air pressures. To obtain a sufficiently large pressure drop regardless of the fuel flow, the size of orifice used was made variable by means of a remotely controlled positioning system.

It should be noted that for the fuel flow trace the deflection is not a linear function of the fuel flow change since the pressure drop across the orifice is proportional to the square of the fuel flow. When obtaining values from the fuel flow trace, it is necessary to adjust for this effect.

The frequency response of this measuring system has not been determined.

Thrust. - The transient thrust measurement like the pressure measurements, was obtained with a strain gage and strain-analyzer-type of amplifier. In this case, however, the strain gage is bonded to a thrust link attached from the engine to the mount. The engine is supported in such a manner that the total force of the engine is transmitted to the mount through this thrust link.

The frequency response of the circuit to a change in the thrust link is limited by the recorder and amplifier, but the response of the entire system is dependent on the dynamics of the entire mounting system, which has not been determined.

Control valve pressure drops. - The pressure drops across the valves in the control were measured by differential strain-gage pressure pickups connected across the valves. The operation of the pressure pickup is again the same as in the case of those used to measure air pressure.

As in the case of fuel flow, the frequency response of this system is undetermined.

APPENDIX B

SYMBOLS

The following symbols are used in this report:

A	engine exhaust-nozzle area
$F(i\omega)$	frequency-response function
$F(p)$	transfer function
$f(t)$	function of time
$f'(t)$	first time derivative of $f(t)$
K	control gain, fuel flow to speed error
K_e	engine gain, engine speed to fuel flow
L	Laplace transform
N	engine speed
N_s	engine speed setting
p	complex number
W_f	engine fuel flow
τ	time constant associated with exhaust-nozzle servo
τ_e	engine lag time constant
τ_1	integral time constant of control
τ_2	time constant of first control lag
τ_3	time constant of second control lag
ω	frequency

Subscripts:

i	input
o	output

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4. Schmidt, Ross D., Vasu, George, and McGraw, Edward W.: Determination of Surge and Stall Limits of an Axial-Flow Turbojet Engine for Control Applications. NACA RM E53B10, 1953.

5. Shepard, Charles E., and Warshawsky, Isidore: Electrical Techniques for Compensation of Thermal Time Lag of Thermocouples and Resistance Wire Thermometer Elements. NACA TN 2703, 1952.

6. Scadron, Marvin D., and Warshawsky, Isidore: Experimental Determination of Time Constants and Nusselt Numbers for Bare-Wire Thermocouples in High-Velocity Air Streams and Analytic Approximation of Conduction and Radiation Errors. NACA TN 2599, 1952.

7. Delio, Gene J., Schwent, Glennon V., and Cesaro, Richard S.: Transient Behavior of Lumped-Constant Systems for Sensing Gas Pressures. NACA TN 1988, 1949.

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TABLE I - INSTRUMENTATION

Measured quantity	Steady-state instrumentation	Transient instrumentation	
		Sensor	Range over which frequency response is essentially flat, cps
Exhaust-nozzle area	Potentiometer attached to rack and gear assembly and connected in electrical circuit to give indication on micro-ammeter; microammeter reading converted to area	Control feedback potentiometer	0-100
Power lever position	Potentiometer actuated by power lever and connected in electrical circuit to give indication on microammeter; microammeter reading converted to degrees	Potentiometer connected to power lever	0-100
Turbine discharge temperature	Twenty-four individual thermocouples connected to self-balancing potentiometer recorder	Six parallel-connected 18-gage chromel-alumel butt-welded thermocouples and electric network to compensate for thermocouple lag	0-5 at sea-level static when used with properly adjusted compensator
Turbine-inlet temperature	Ten individual traversing probes, sonic-type shielded thermocouples, connected to a self-balancing potentiometer recorder	Five sonic-type shielded thermocouples in series	0-0.265 at sea-level static
Engine speed	Modified electronic tachometer	Modified electronic tachometer	0-10
Engine acceleration	Calibration obtained from transient speed traces	Modified electronic tachometer and differentiating circuit	0-2
Ram pressure	Water manometers	Aneroid-type pressure sensor with strain-gage element	0-10 at sea-level static
Dynamic pressure at engine inlet	Water manometers	Aneroid-type pressure sensor with strain-gage element	0-10 at sea-level static
Compressor discharge total pressure	Mercury manometers	Aneroid-type pressure sensor with strain-gage element	0-10 at sea-level static
Turbine-discharge total pressure	Alkazene manometers	Aneroid-type pressure sensor with strain-gage element	0-10 at sea-level static
Thrust	Scale	Strain gage mounted on strain link attached to forward engine suspension	0-100
Fuel flow	Rotameter	Aneroid-type pressure sensor with strain-gage element connected to measure pressure drop across a variable orifice in the fuel line	Undetermined
Pressure drop across throttle valve	Calibration obtained from static pressure tests of transient equipment	Aneroid-type pressure sensor with strain-gage element	Undetermined
Pressure drop across acceleration valve	Calibration obtained from static pressure tests of transient equipment	Aneroid-type pressure sensor with strain-gage element	Undetermined
Pressure drop across overspeed valve	Calibration obtained from static pressure tests of transient equipment	Aneroid-type pressure sensor with strain-gage element	Undetermined
Pressure drop across all three control valves	Calibration obtained from static pressure tests of transient equipment	Aneroid-type pressure sensor with strain-gage element	Undetermined
Compressor pressure rise	Steady-state values of compressor-inlet pressure subtracted from steady-state values of compressor-discharge pressure	Aneroid-type pressure sensor with strain-gage element	0-10 at sea-level static

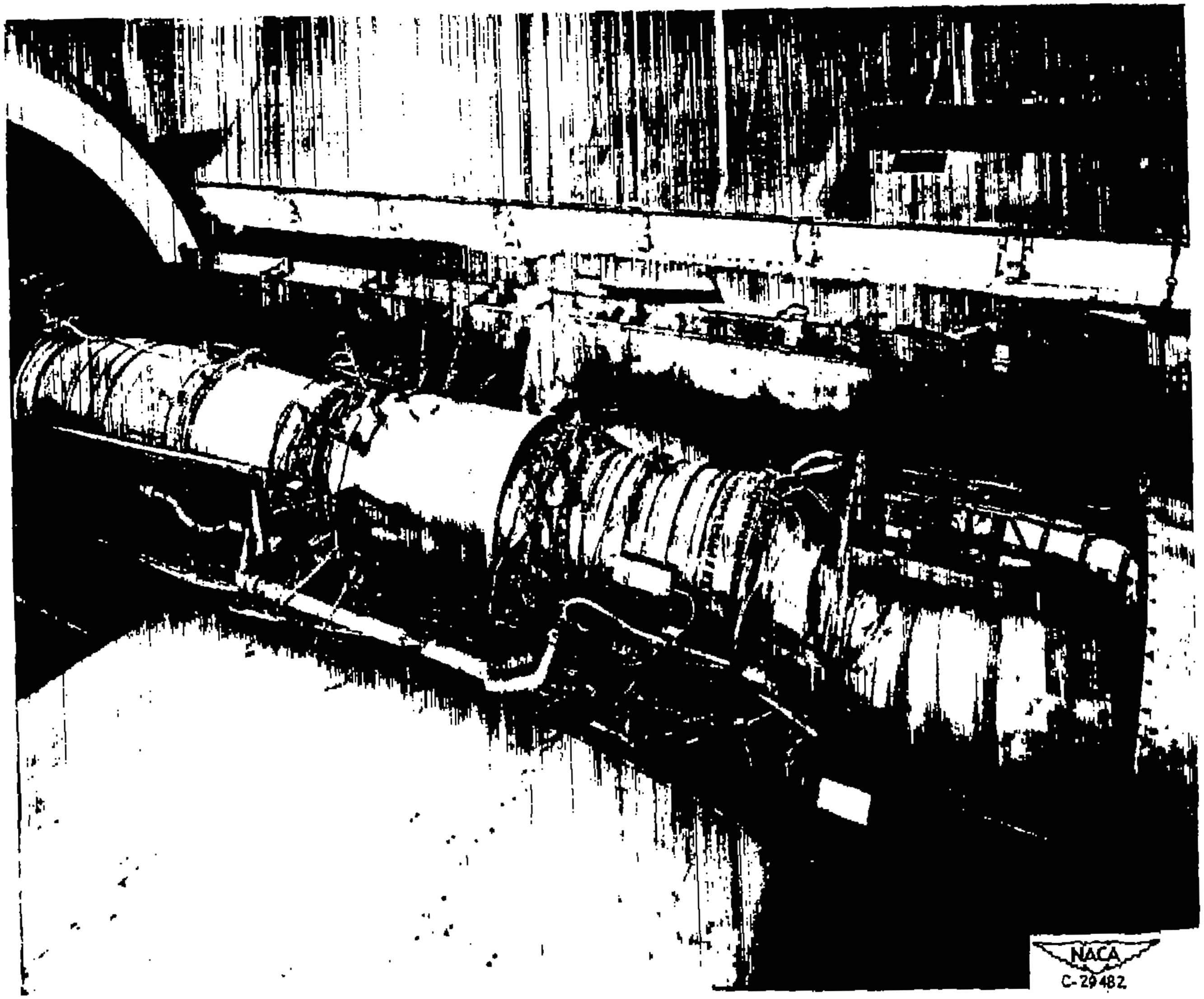

Figure 1. - Turbojet engine with afterburner installation in NACA altitude wind tunnel.

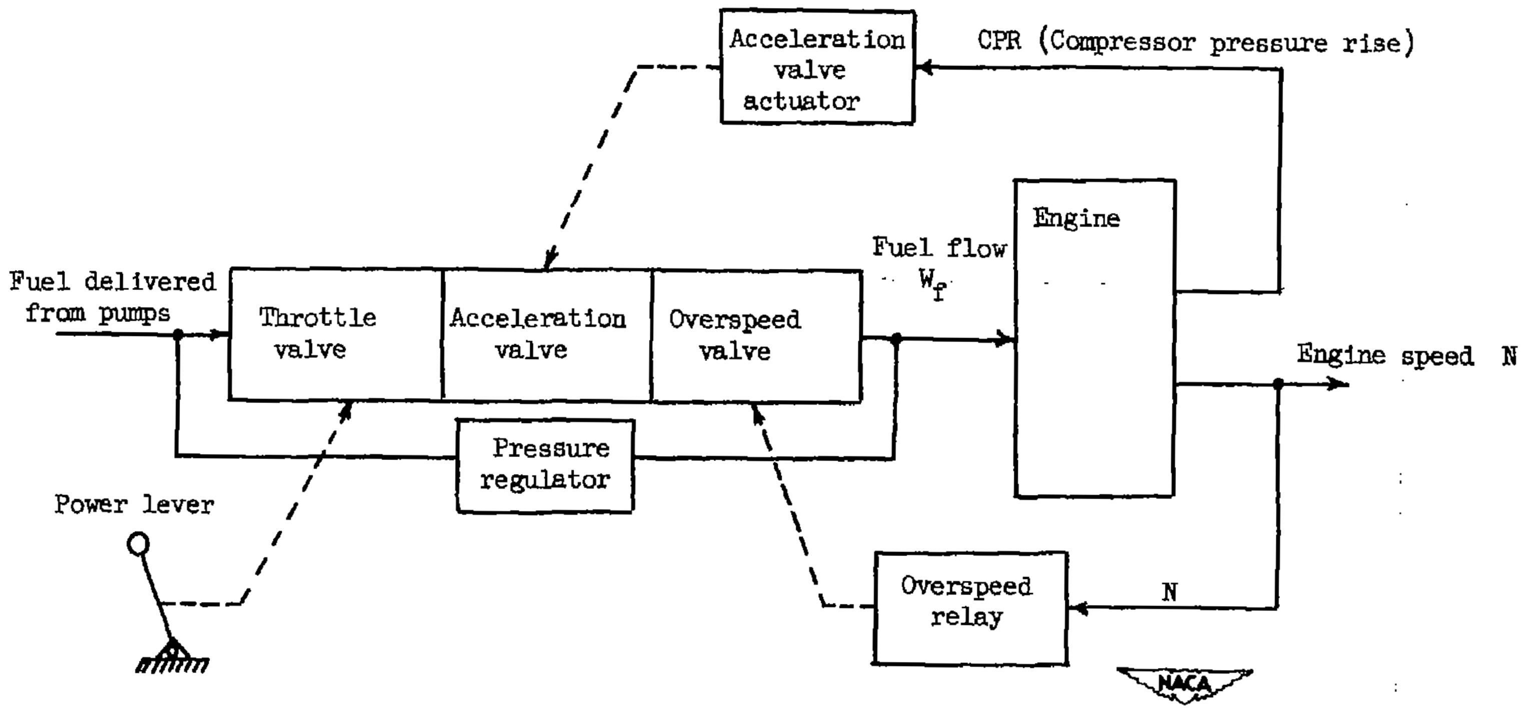

Figure 2. - Block diagram of engine and hydraulic control.

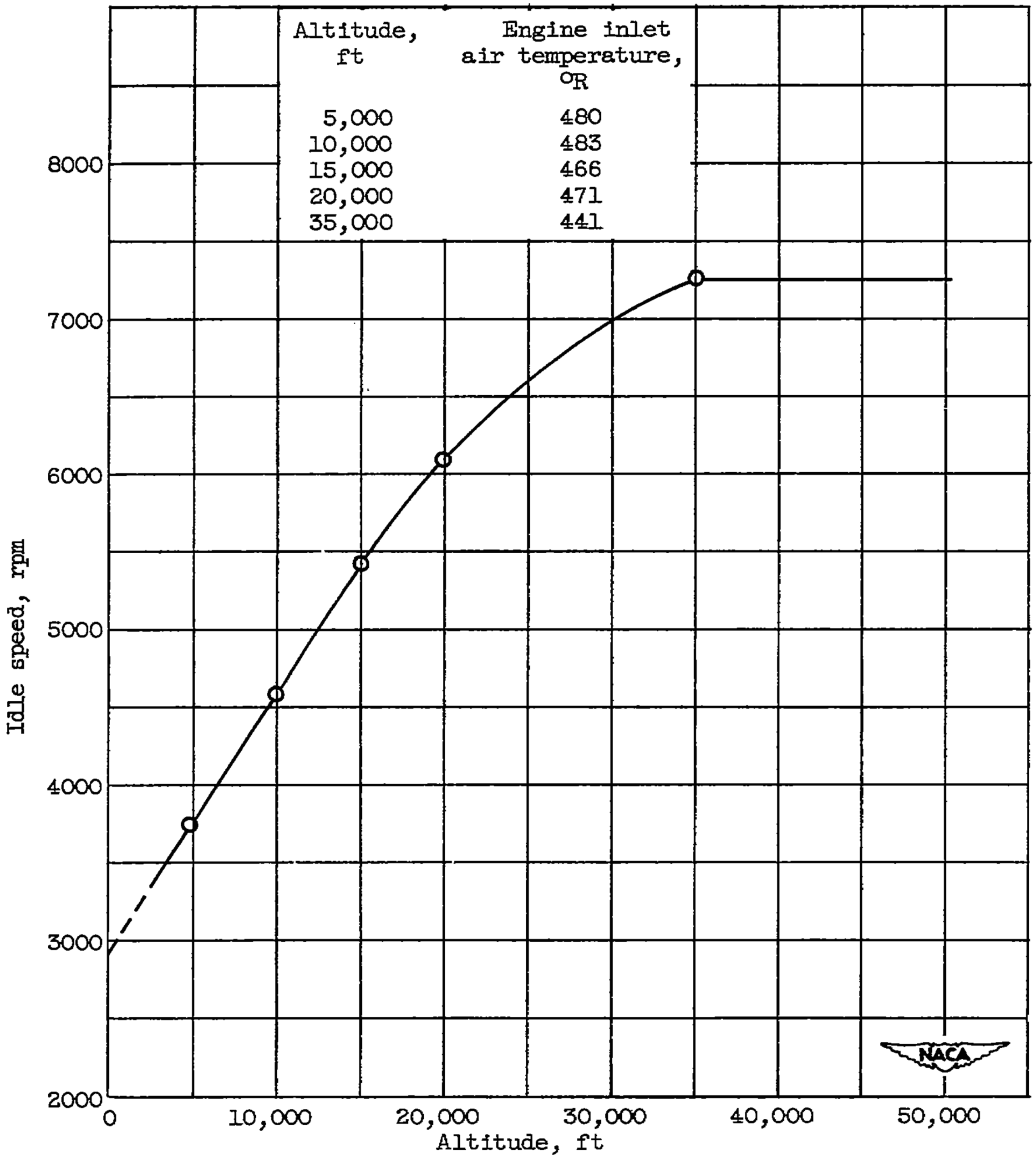

Figure 3. - Variation of idle speed with altitude for controlled engine at ram pressure ratio of 1.02.

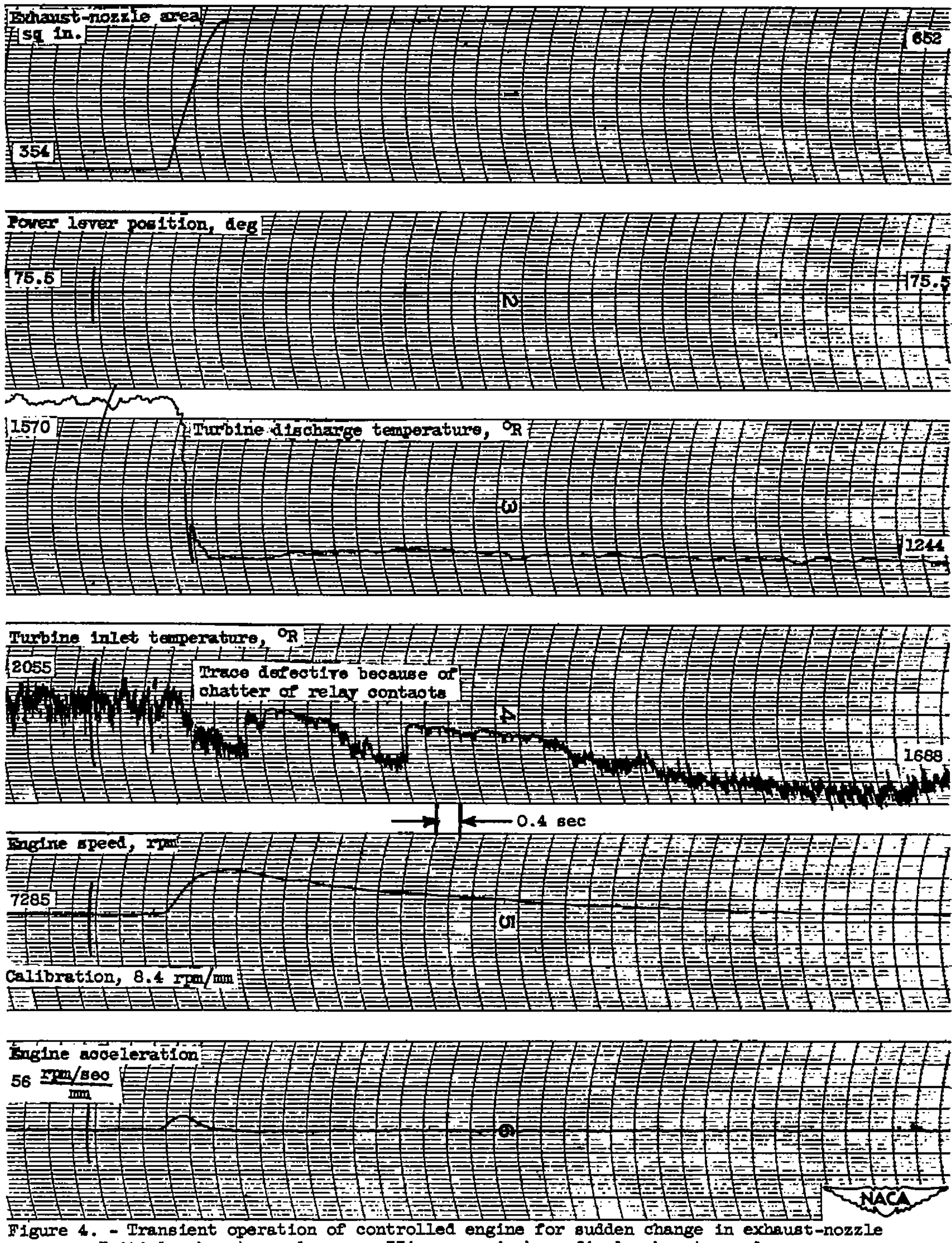

Figure 4. - Transient operation of controlled engine for sudden change in exhaust-nozzle area. Initial exhaust-nozzle area, 354 square inches; final exhaust-nozzle area, 652 square inches; altitude, 15,000 feet; nominal ram pressure ratio, 1.02; engine-inlet air temperature, 476° R.

[redacted]

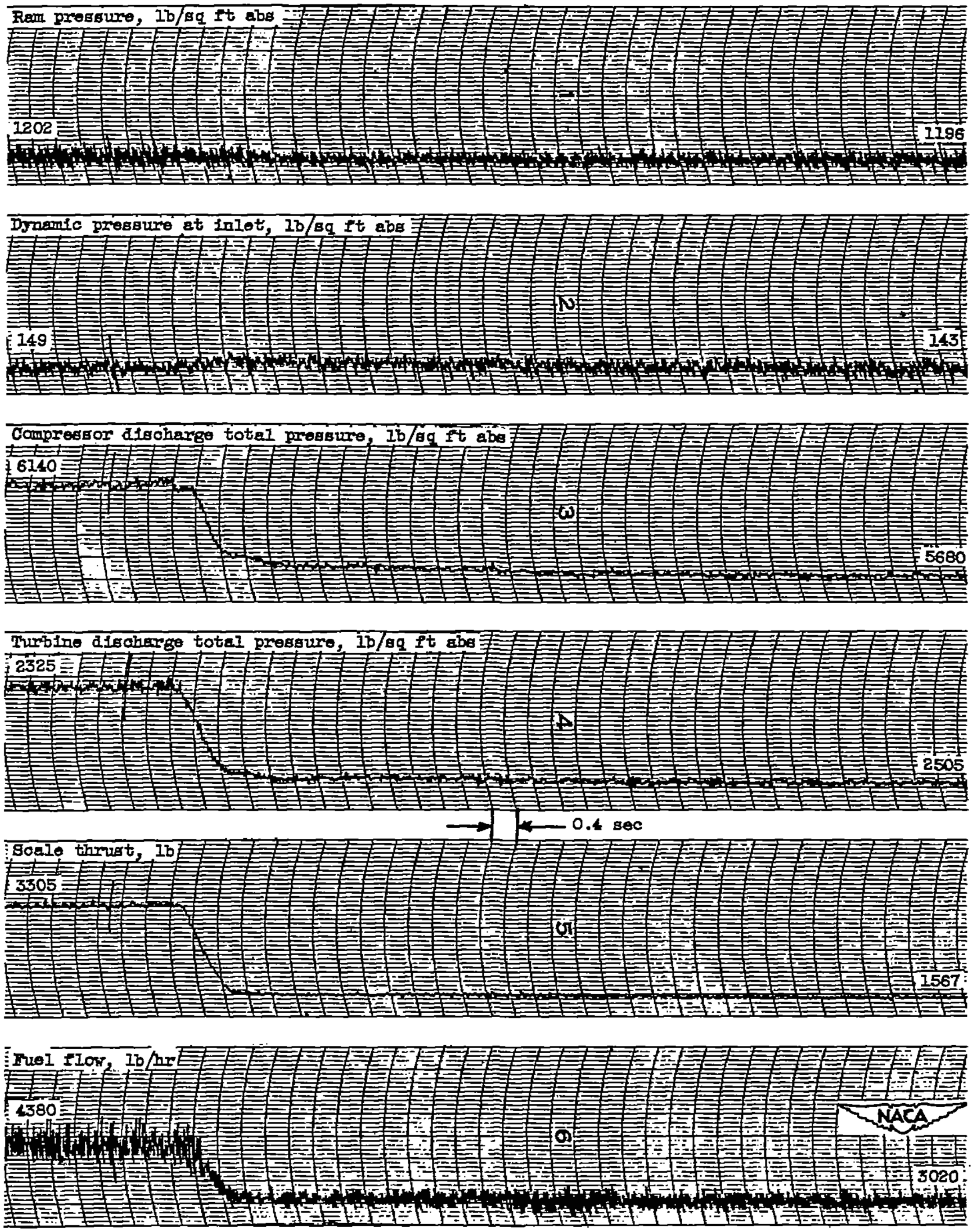

Figure 4. - Continued. Transient operation of controlled engine for sudden change in exhaust-nozzle area. Initial exhaust-nozzle area, 354 square inches; final exhaust-nozzle area, 652 square inches; altitude, 15,000 feet; nominal ram pressure ratio, 1.02; engine-inlet air temperature, 476° R.

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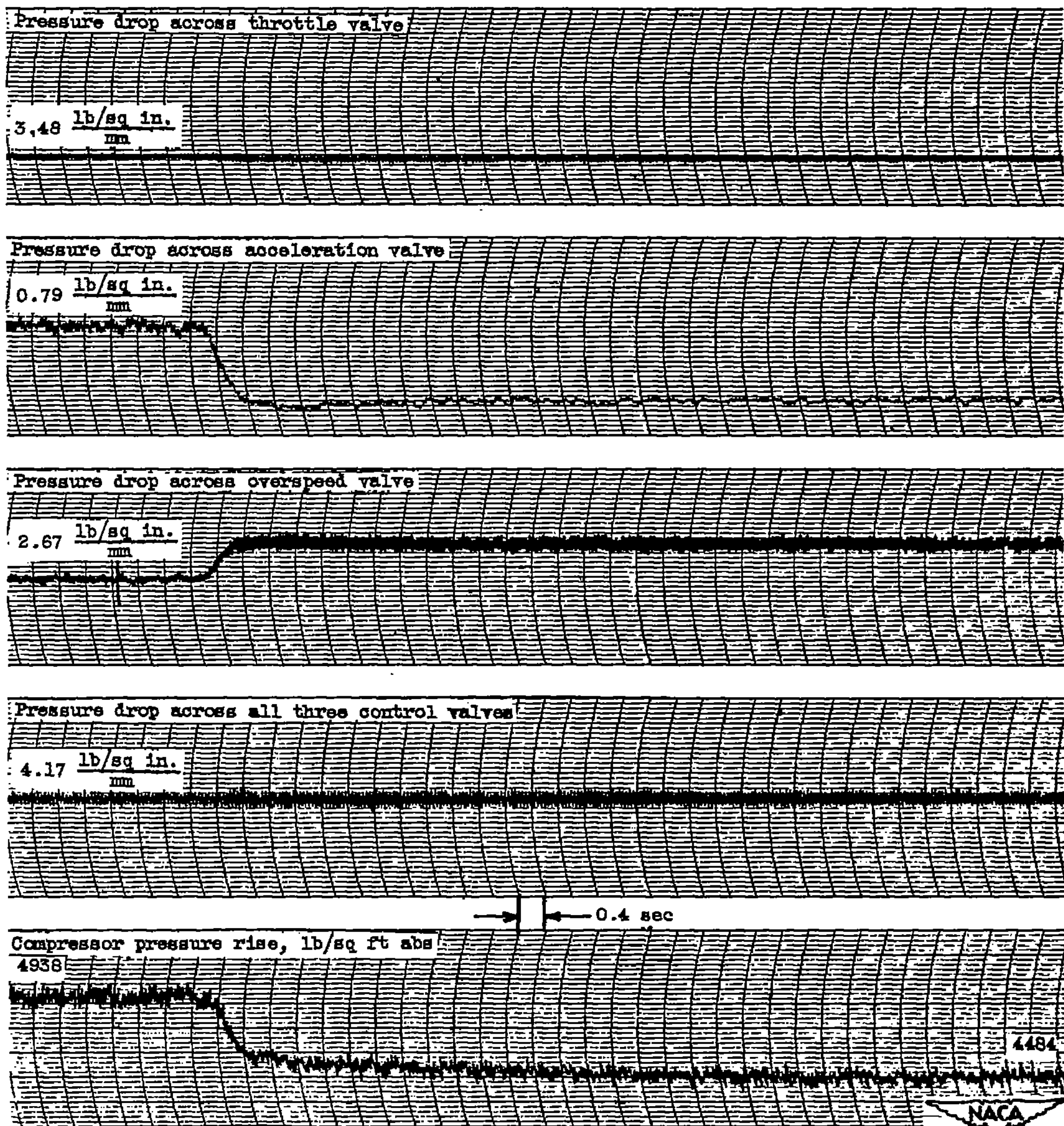

Figure 4. - Concluded. Transient operation of controlled engine for sudden change in exhaust-nozzle area. Initial exhaust-nozzle area, 354 square inches; final exhaust-nozzle area, 652 square inches; altitude, 15,000 feet; nominal ram pressure ratio, 1.02; engine-inlet air temperature, 476° R.

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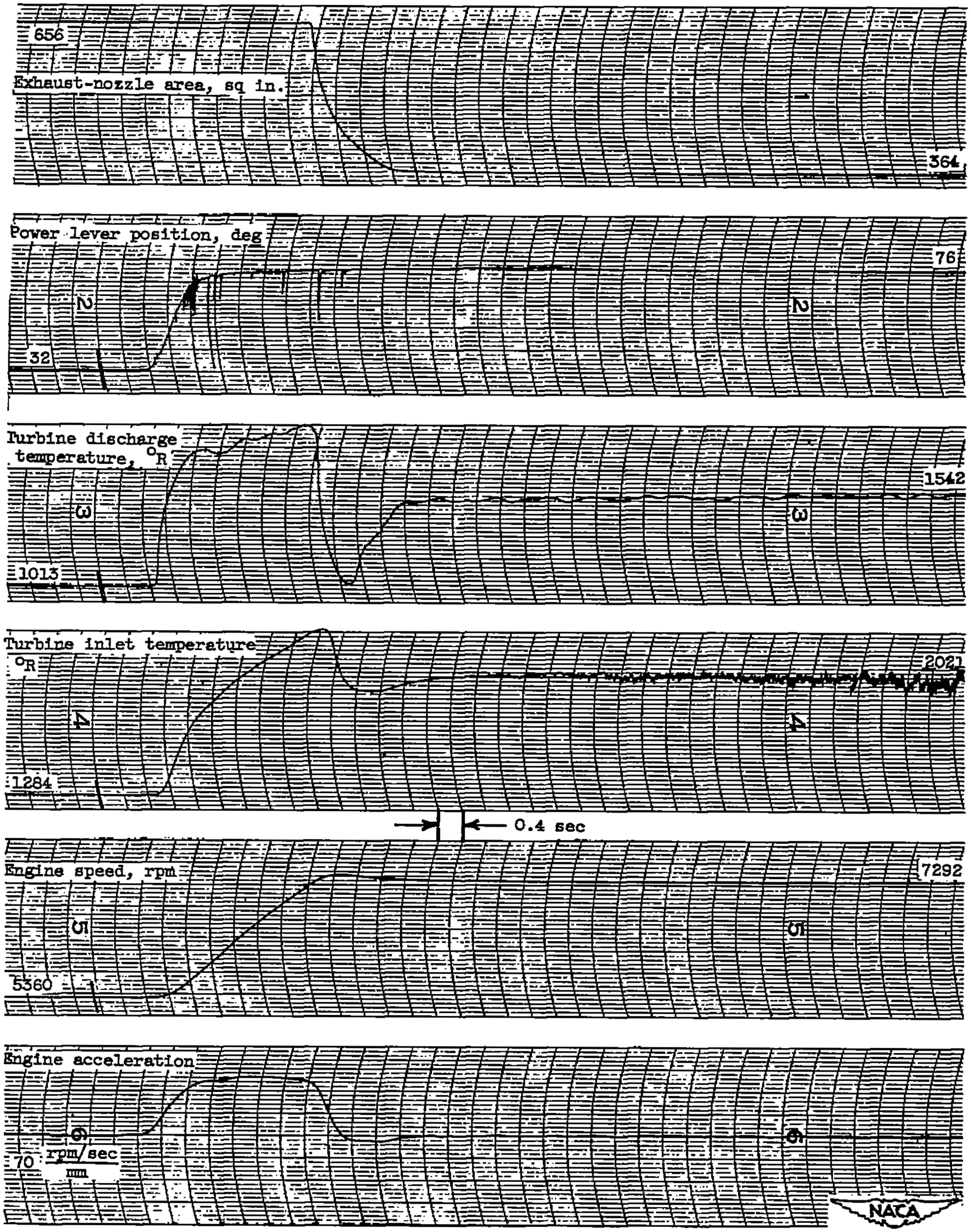

Figure 5. - Transient operation of controlled engine during throttle burst acceleration to full military thrust at original surge control setting. Initial engine speed, 5360 rpm; altitude, 15,000 feet; nominal ram pressure ratio, 1.02; engine-inlet air temperature, 466° R.

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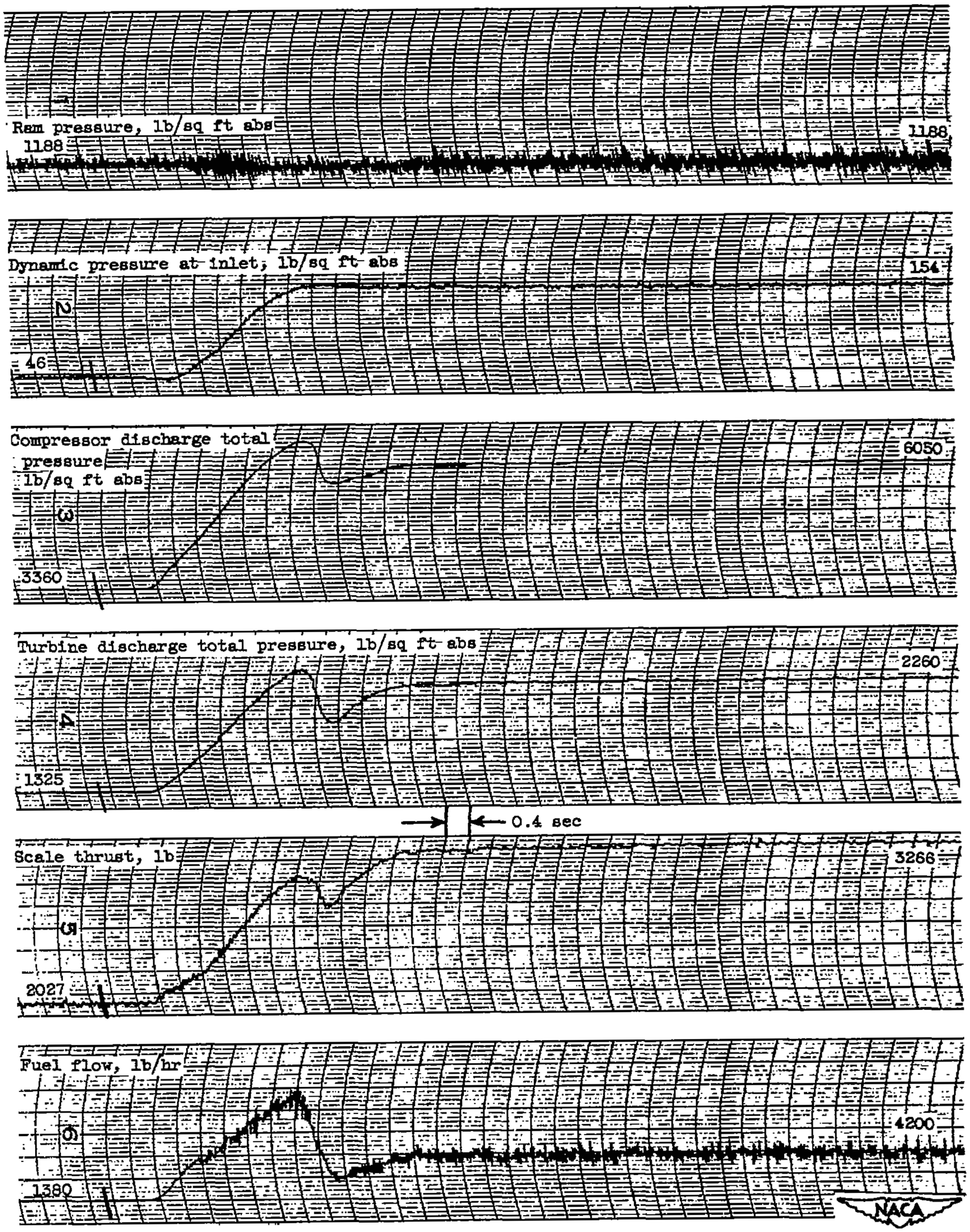

Figure 5. - Continued. Transient operation of controlled engine during throttle-burst acceleration to full military thrust at original surge control setting. Initial engine speed, 5360 rpm; altitude, 15,000 feet; nominal ram pressure ratio, 1.02; engine-inlet air temperature, 466° R.

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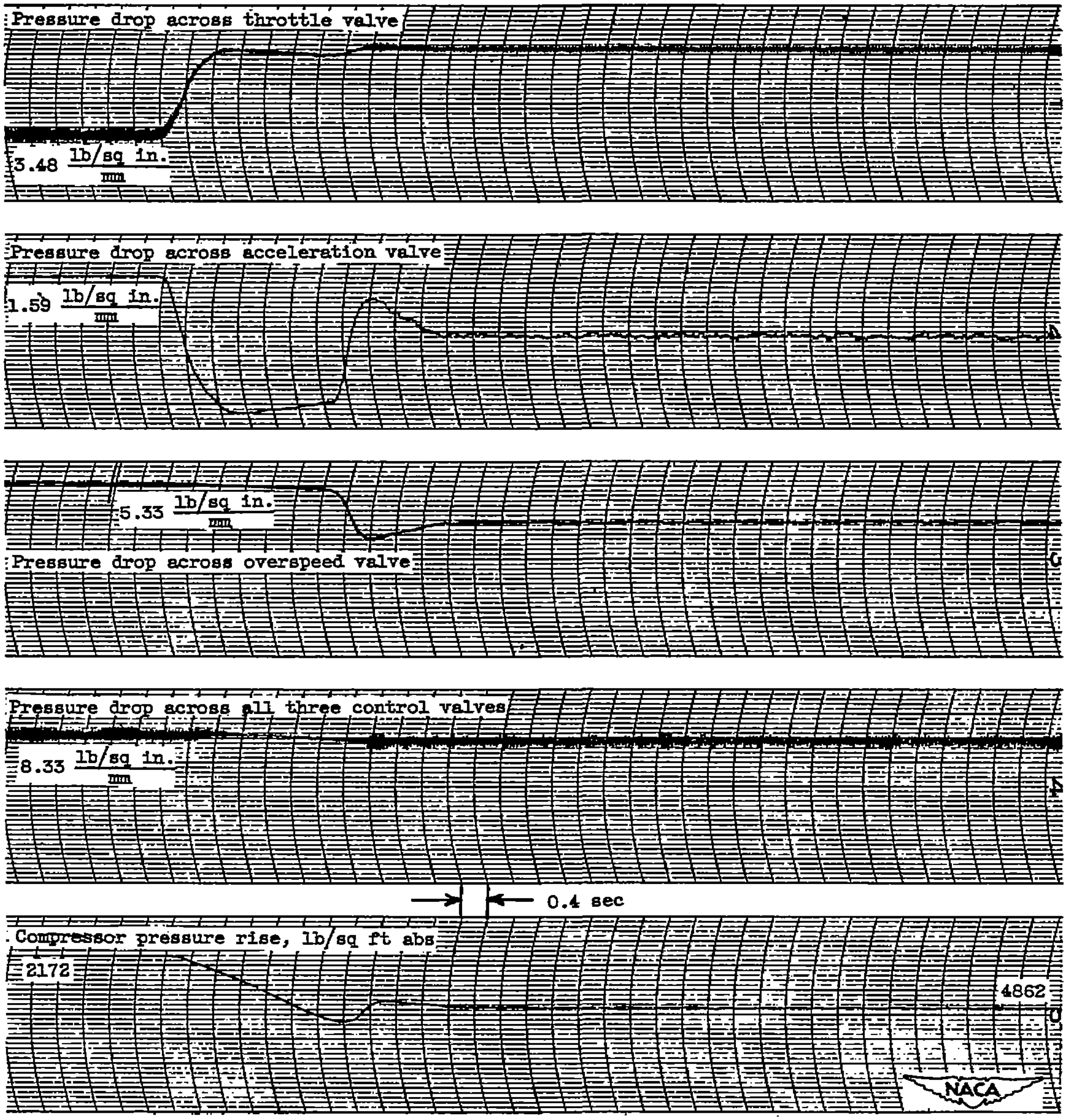
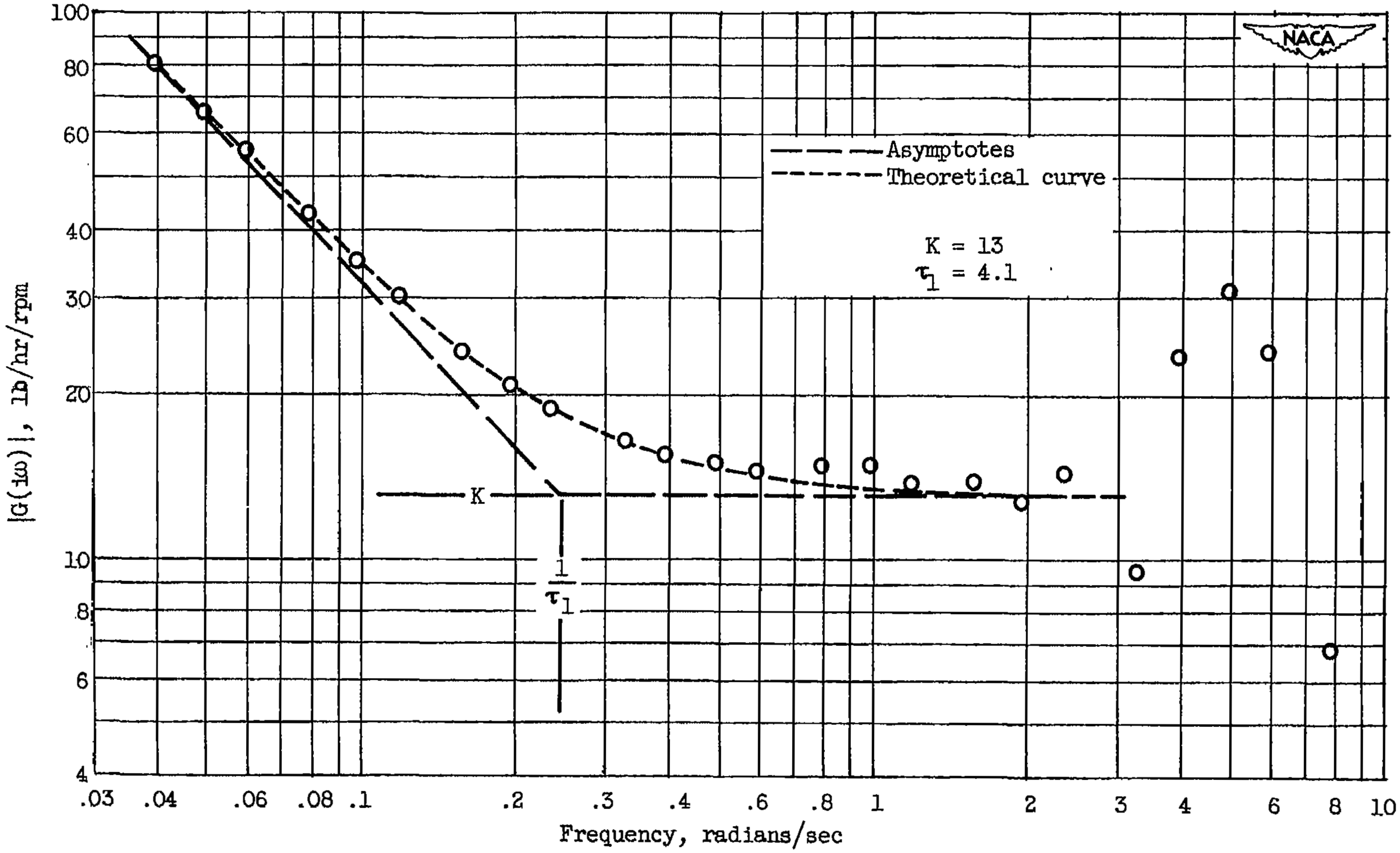
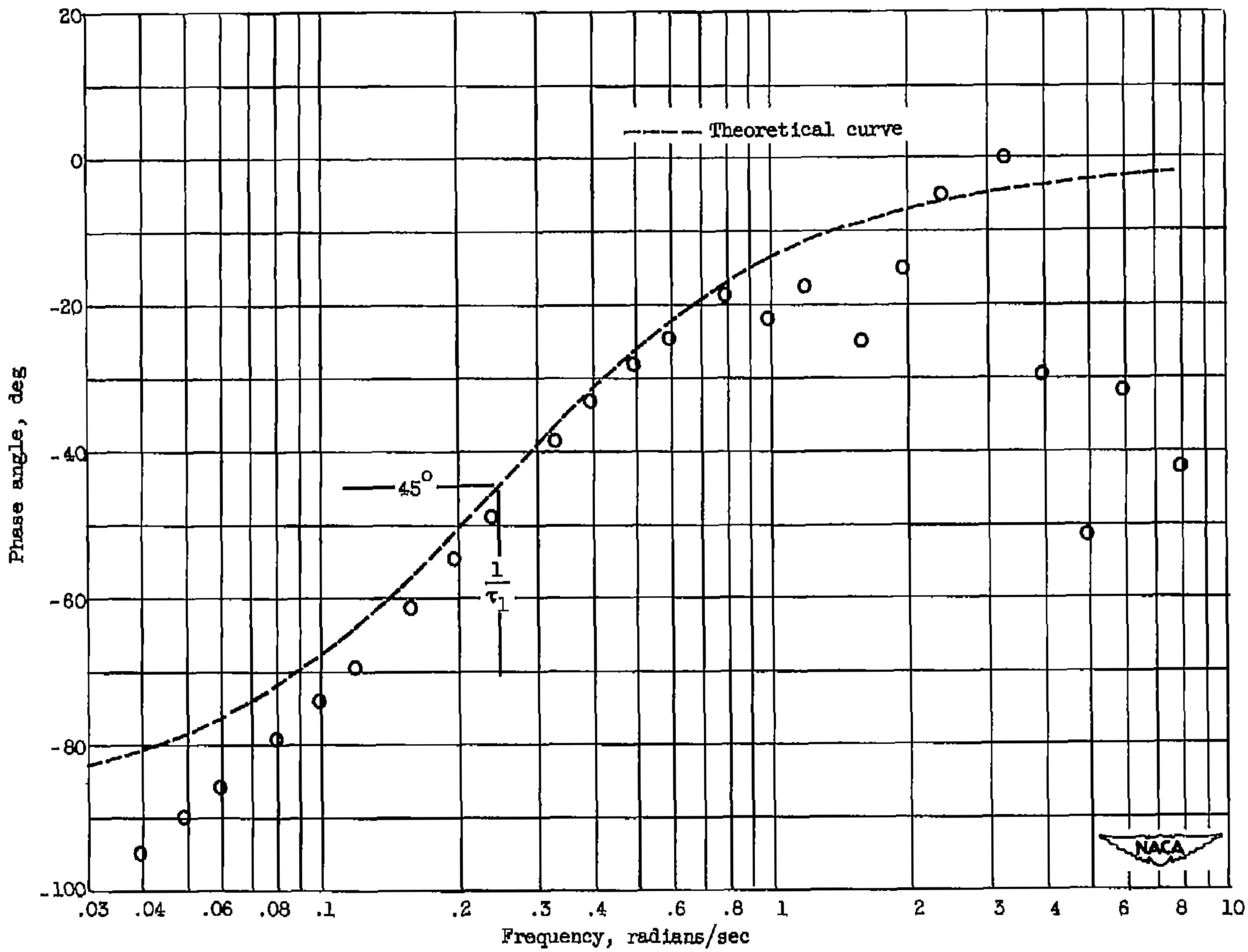


Figure 5. - Concluded. Transient operation of controlled engine during throttle burst acceleration to full military thrust at original surge control setting. Initial engine speed, 5360 rpm; altitude, 15,000 feet; nominal ram pressure ratio, 1.02; engine-inlet air temperature, 466° R.



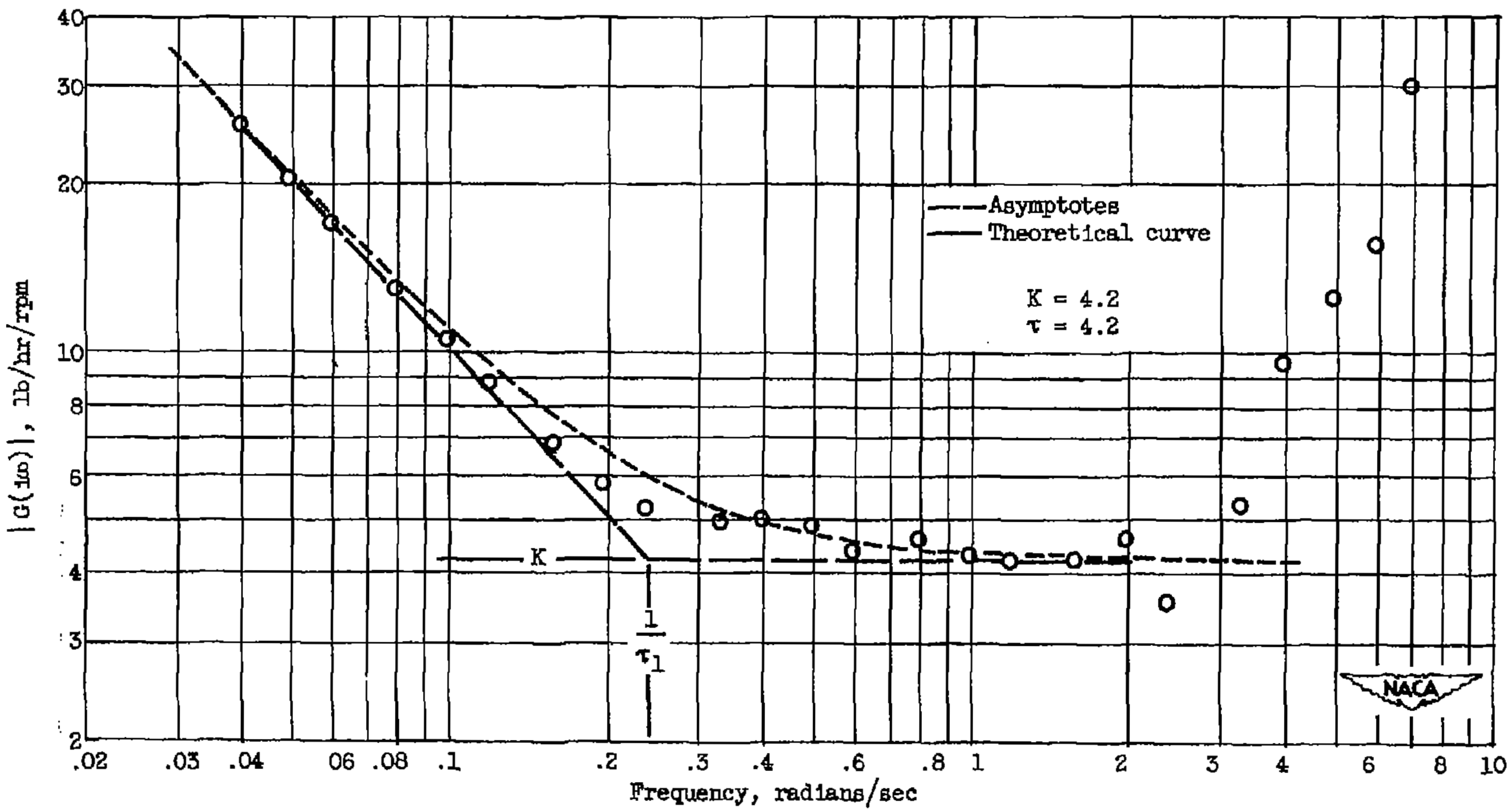
(a) Attenuation characteristics.

Figure 6. - Frequency response of fuel flow to speed error for speed control at altitude of 15,000 feet and ram pressure ratio of 1.02.



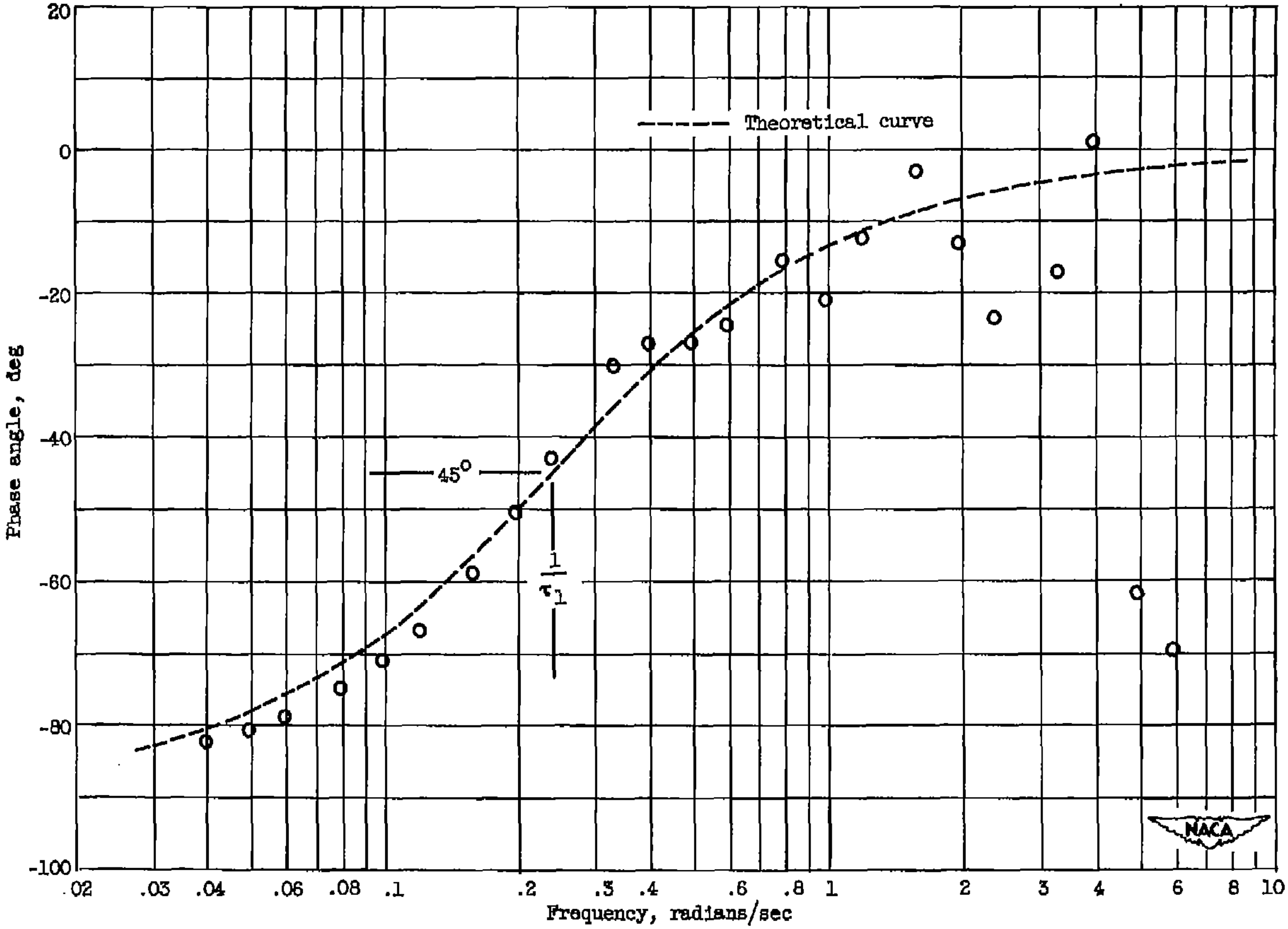
(b) Phase shift characteristics.

Figure 6. - Concluded. Frequency response of fuel flow to speed error for speed control at altitude of 15,000 feet and ram pressure ratio of 1.02.



(a) Attenuation characteristics.

Figure 7 - Frequency response of fuel flow to speed error for speed control at altitude of 35,000 feet and ram pressure ratio of 1.02.



(b) Phase angle characteristics.

Figure 7. - Concluded. Frequency response of fuel flow to speed error for speed control at altitude of 35,000 feet and ram pressure ratio of 1.02.

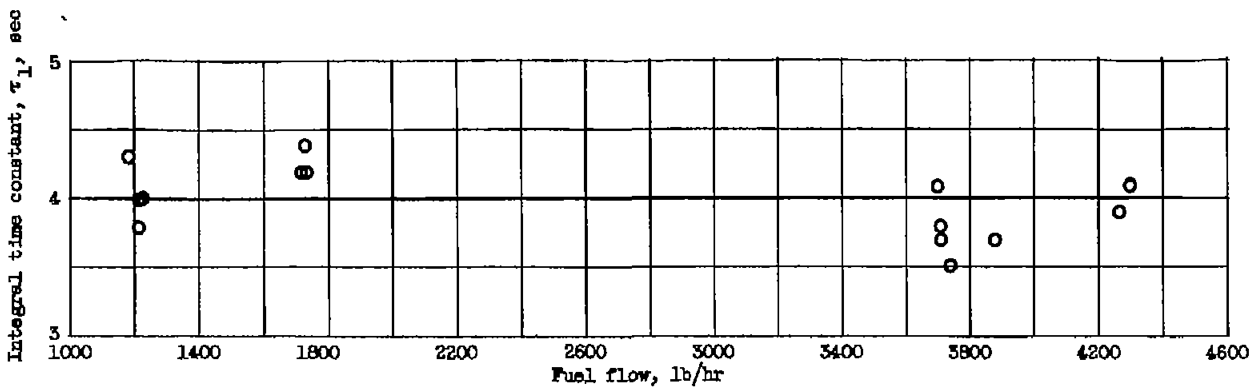


Figure 8. - Variation of integral time constant of speed control with fuel flow.

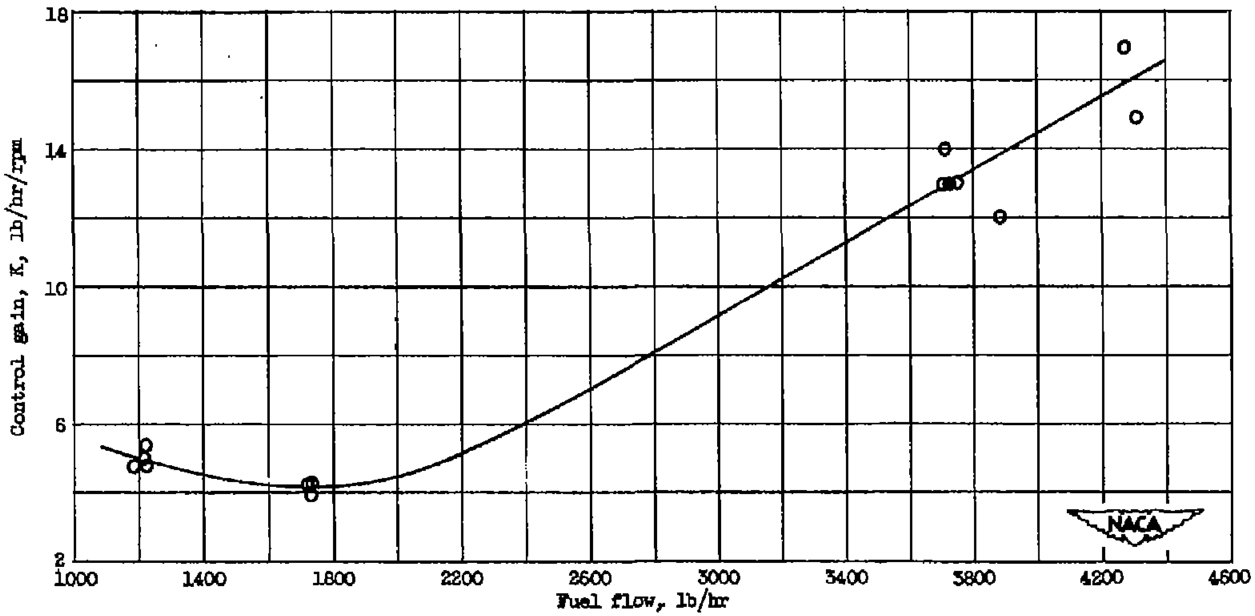


Figure 9. - Variation of fuel flow to speed error gain of speed control with fuel flow.

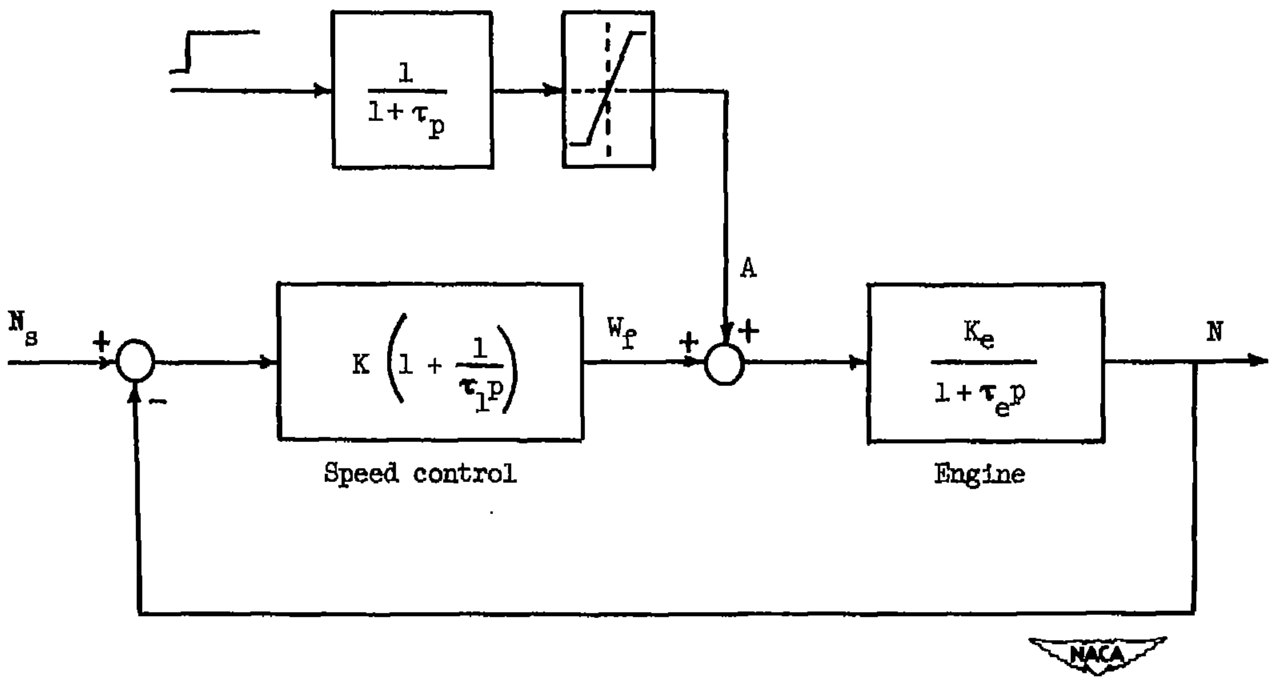


Figure 10. - Block diagram illustrating method of simulating controlled engine for disturbance in exhaust-nozzle area.

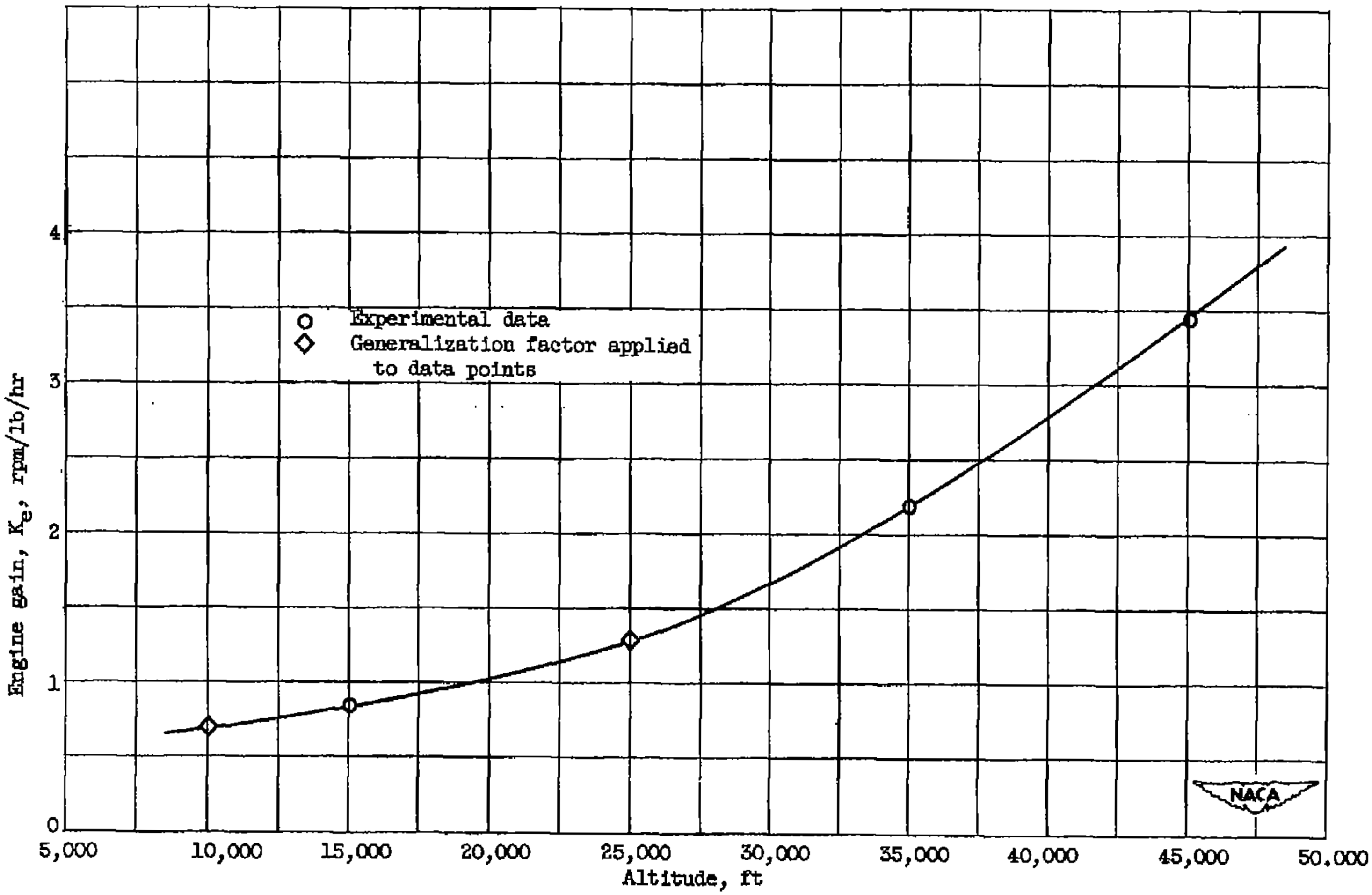


Figure 11. - Variation of speed to fuel flow gain of engine with altitude for operation at full speed with wide open exhaust nozzle at ram pressure ratio of 1.02.

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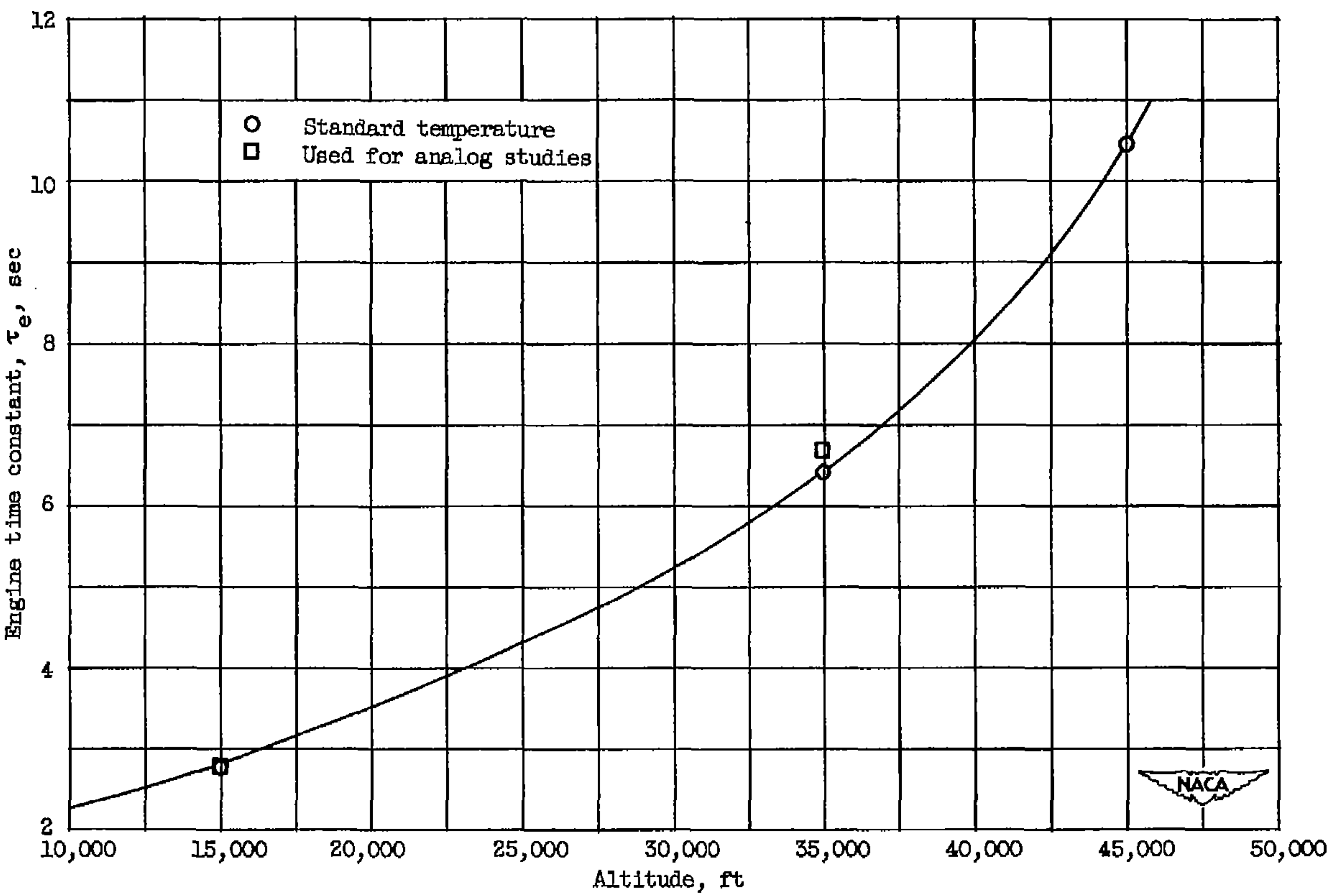

Figure 12. - Variation of engine time constant with altitude for operation at full speed and ram pressure ratio of 1.02.

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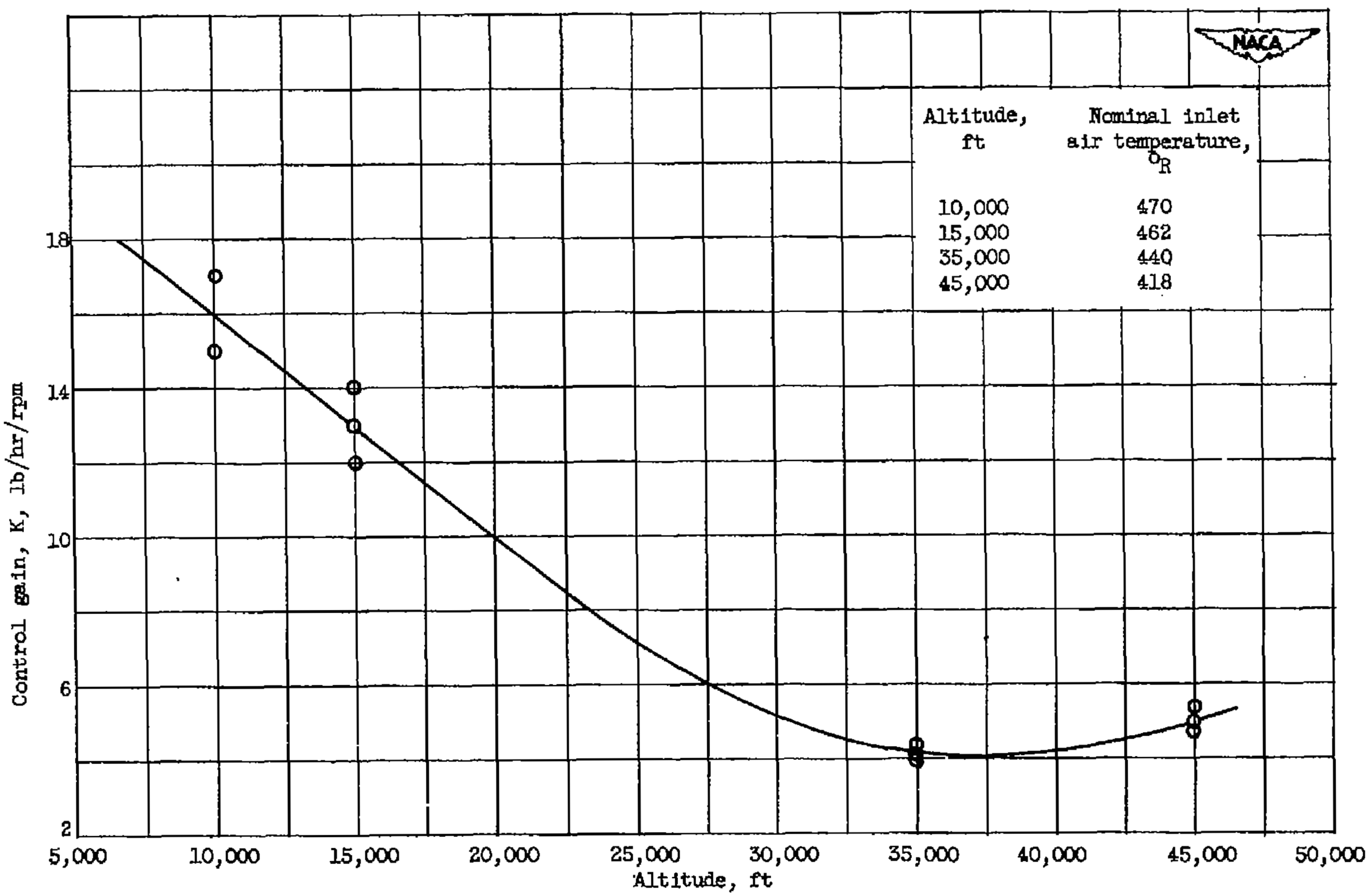

Figure 13. - Variation of control gain of speed control with altitude for operation at ram pressure ratio of 1.02.

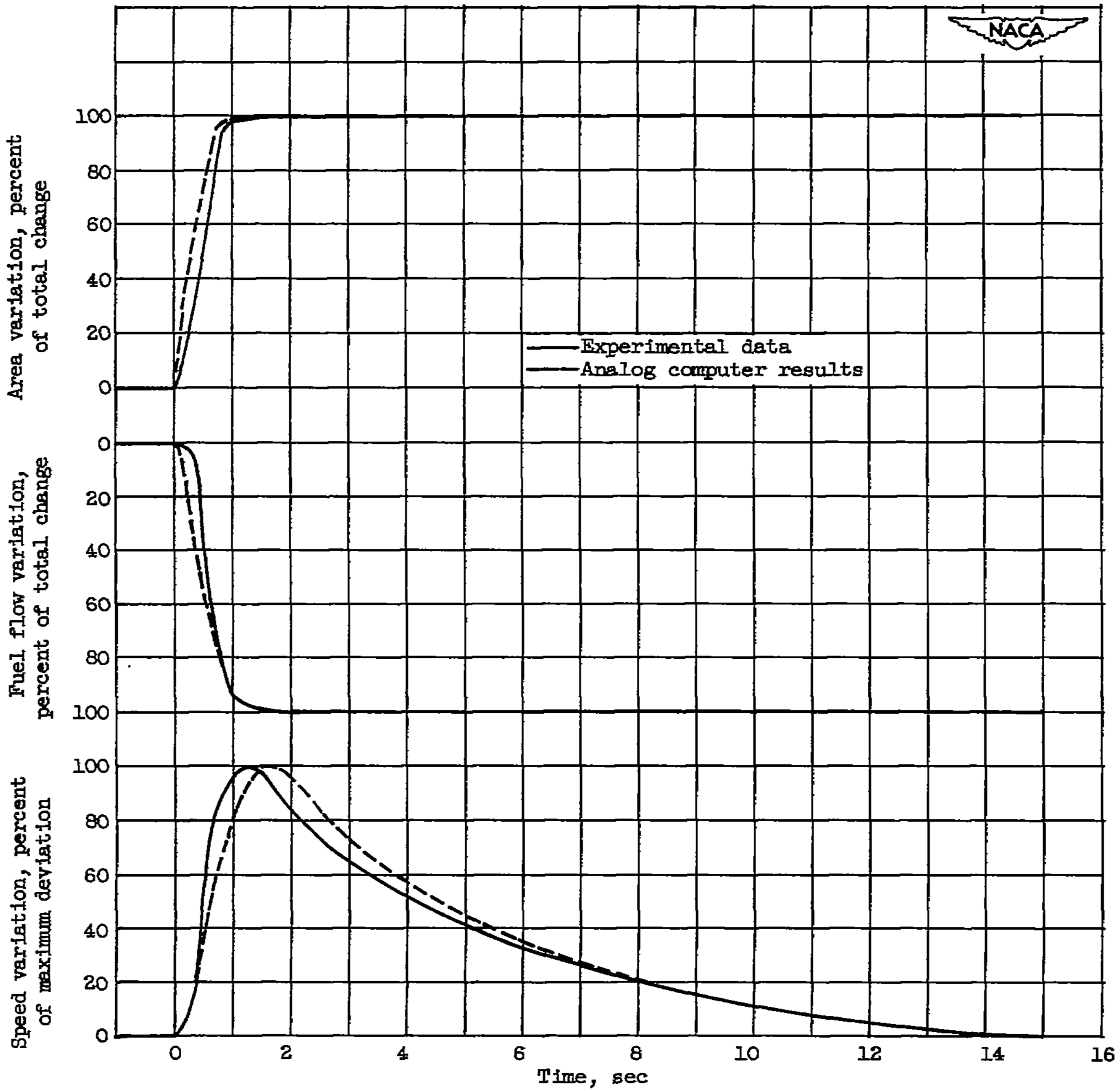

Figure 14. - Comparison of analog computer results with experimental data for transient response of controlled engine to sudden change in exhaust-nozzle area at altitude of 15,000 feet, ram pressure ratio of 1.02, and standard engine-inlet air temperature.

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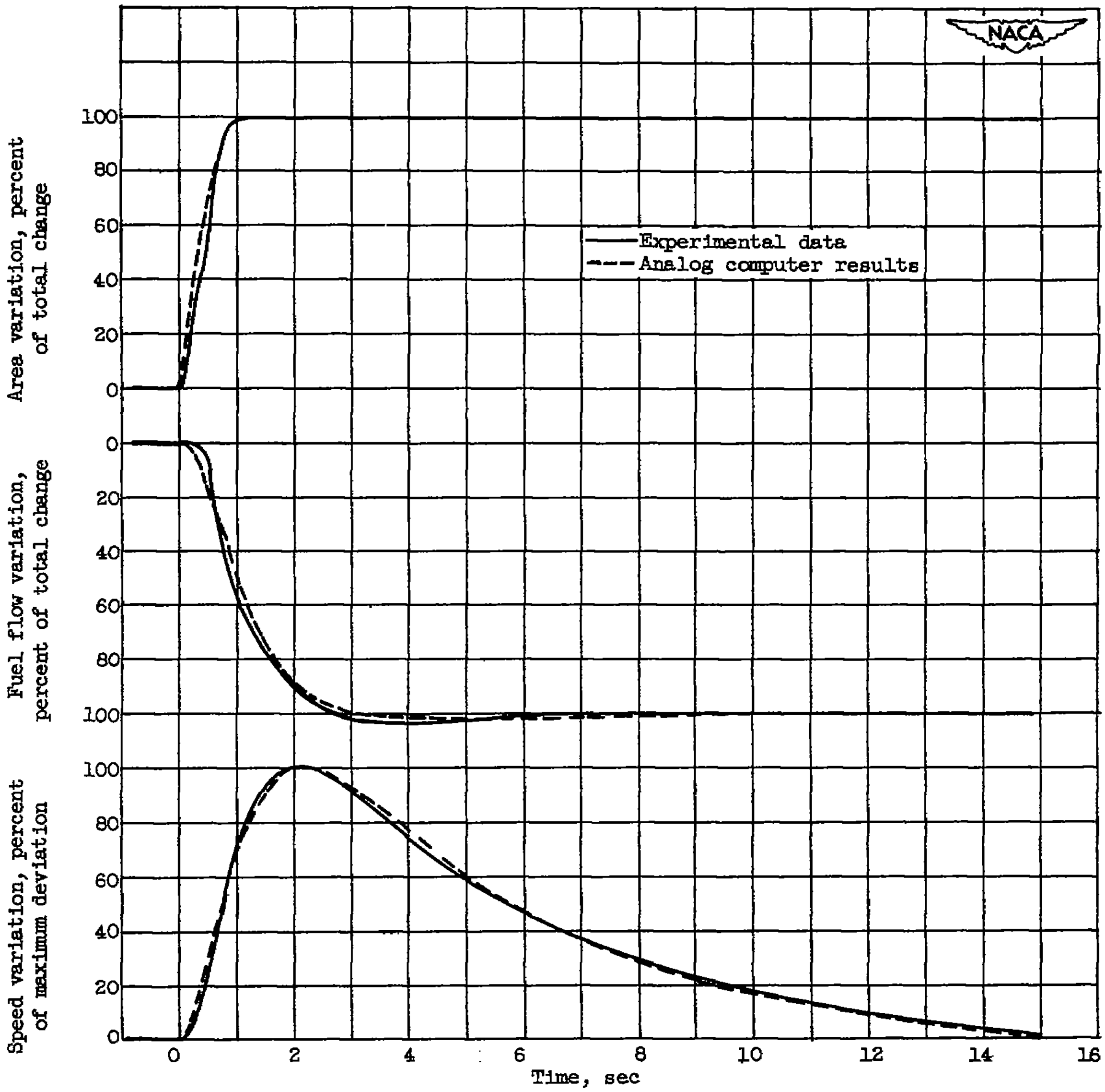

Figure 15. - Comparison of analog computer results with experimental data for transient response of controlled engine to sudden change in exhaust-nozzle area at altitude of 35,000 feet, ram pressure ratio of 1.02, and engine-inlet air temperature of 444° R.

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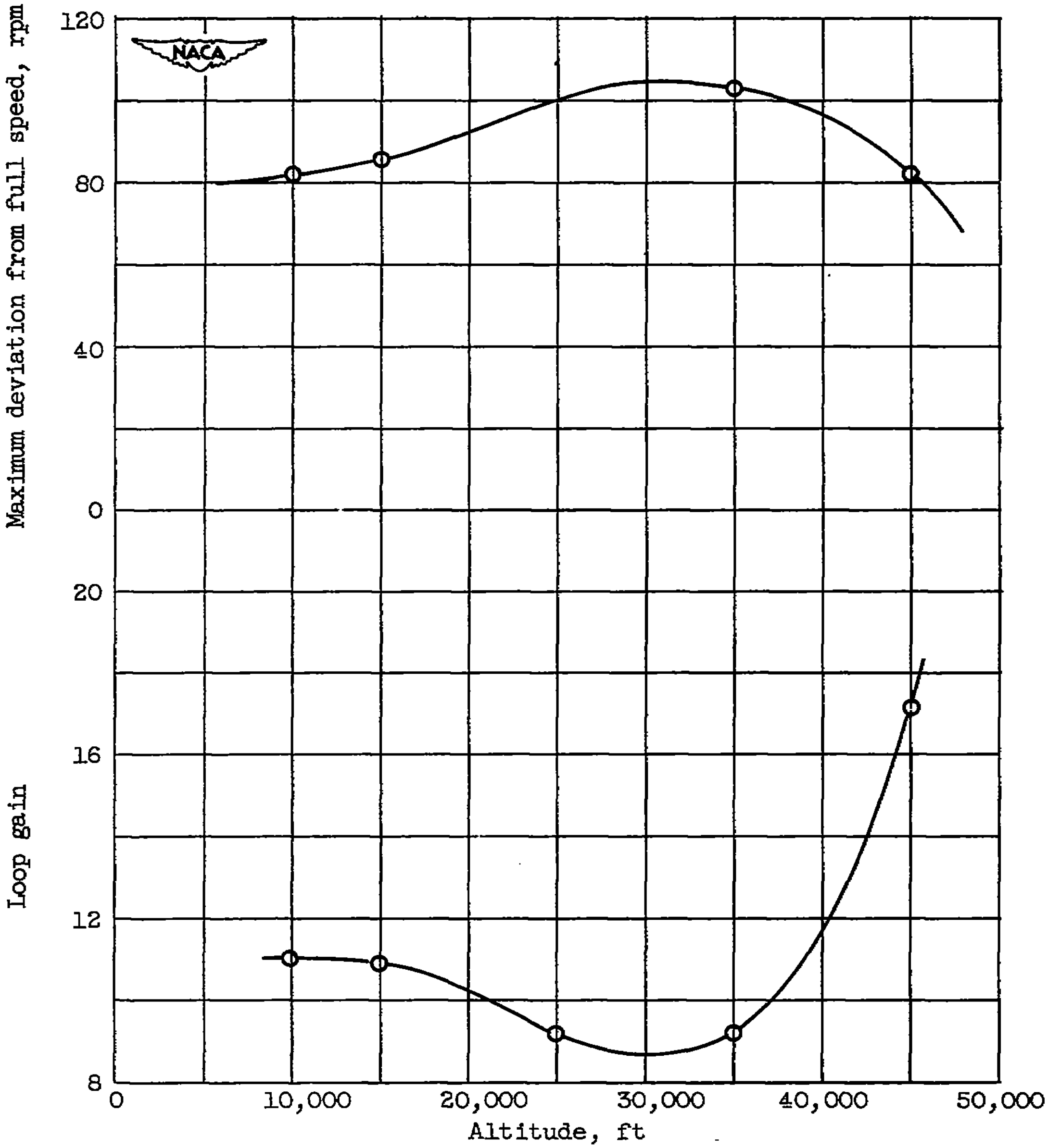


Figure 16. - Comparison of variation with altitude of maximum speed error following exhaust-nozzle disturbances and loop gain of controlled engine at constant ram pressure ratio.

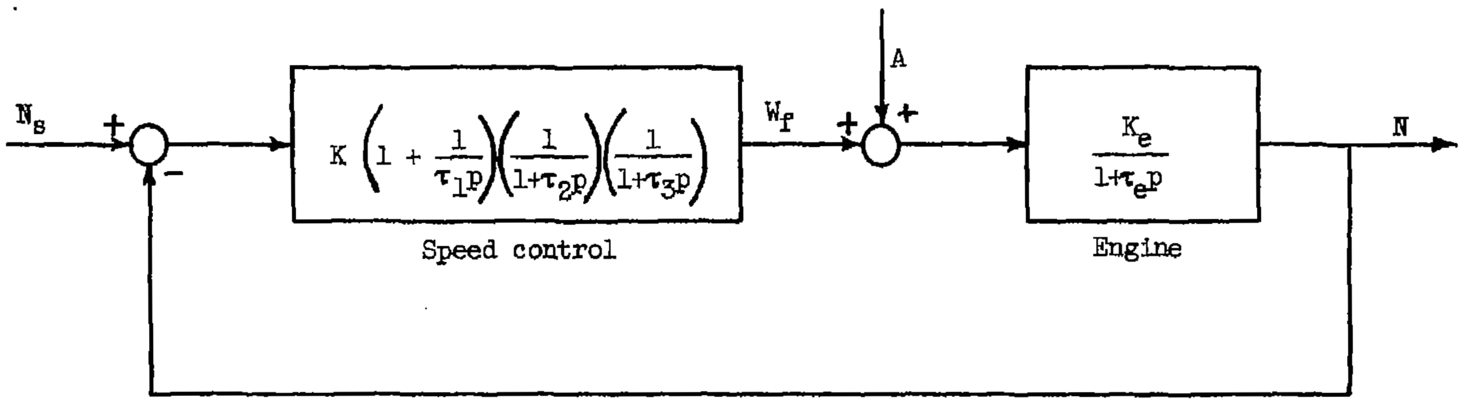
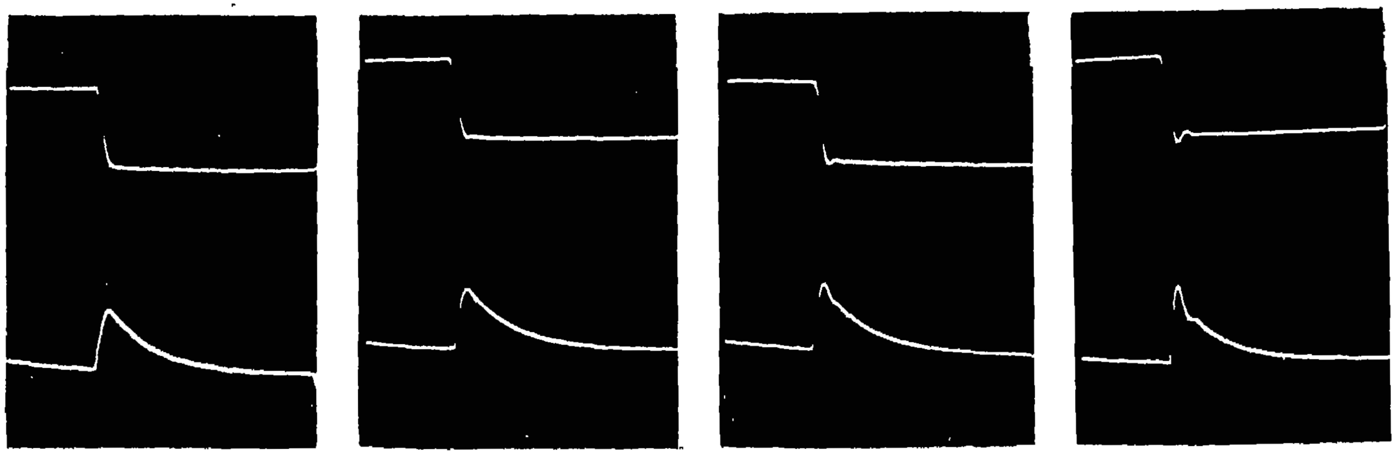


Figure 17. - Block diagram of analog computer illustrating functions used for study of effect of high frequency terms on response of simulated controlled engine.



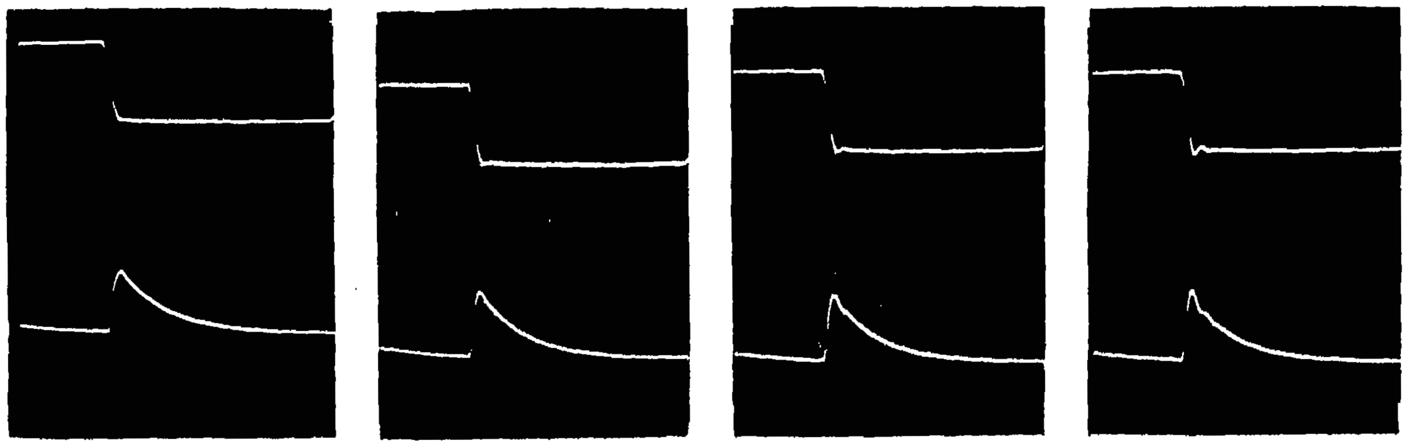
(a) $\tau_2 = 0$; $\tau_3 = 0$.

(b) $\tau_2 = 0.1$ second; $\tau_3 = 0$.

(c) $\tau_2 = 0.2$ second; $\tau_3 = 0$.

(d) $\tau_2 = 0.3$ second; $\tau_3 = 0$.

[redacted]



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(e) $\tau_2 = 0.1$ second; $\tau_3 = 0$.

(f) $\tau_2 = 0.1$ second; $\tau_3 = 0.03$ second.

(g) $\tau_2 = 0.1$ second; $\tau_3 = 0.05$ second.

(h) $\tau_2 = 0.1$ second; $\tau_3 = 0.1$ second.

Figure 18. - Computer fuel flow and engine speed responses illustrating effect of additional lags. Altitude, 15,000 feet; engine time constant τ_e, 2.8 seconds. Upper trace in each figure, fuel flow; lower trace, engine speed.

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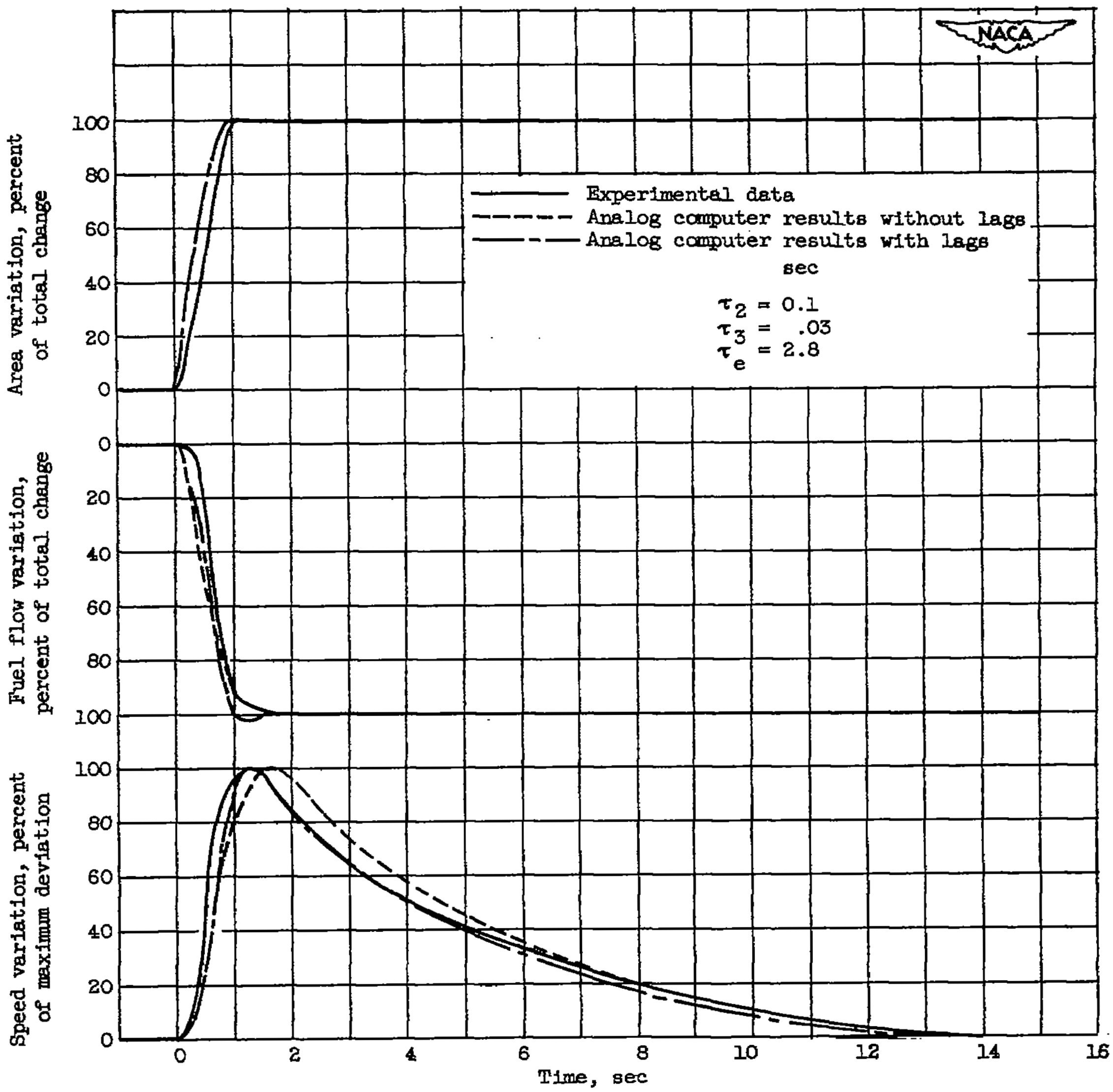
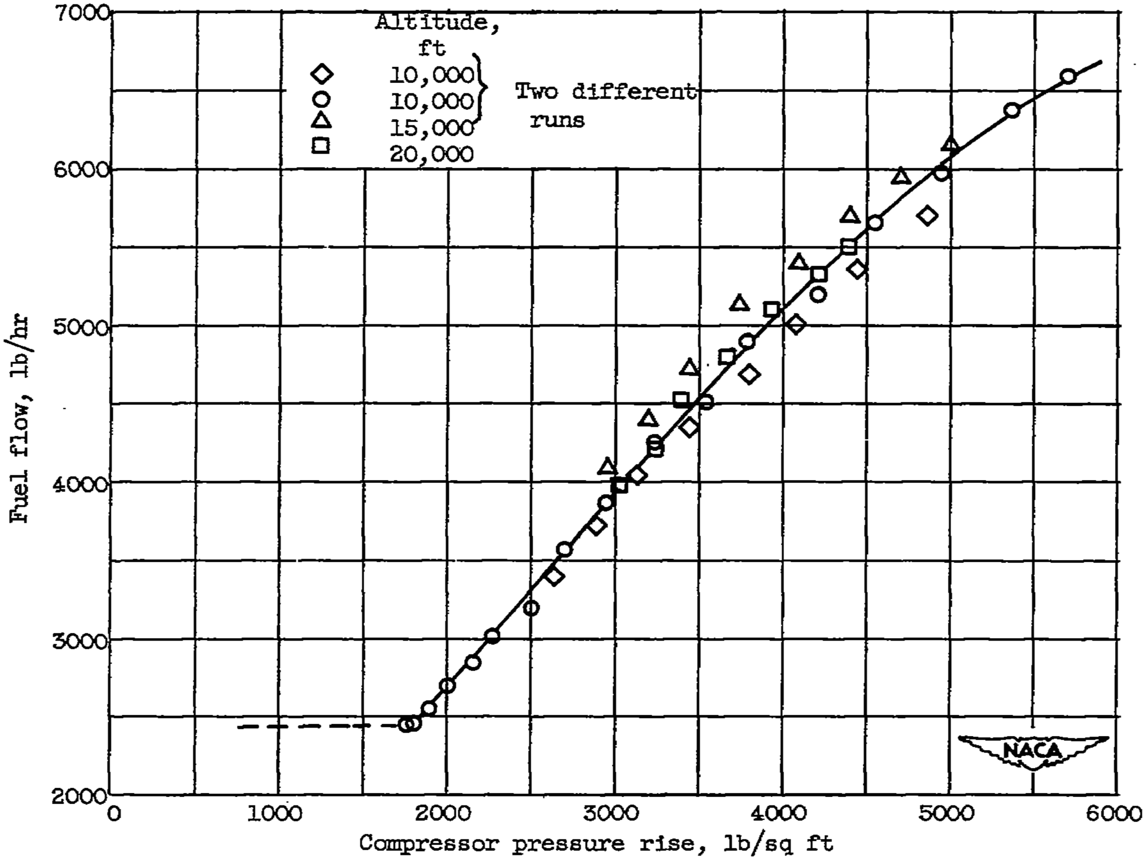


Figure 19. - Comparison of analog computer responses with and without lags with experimental responses for altitude of 15,000 feet.



(a) First setting of acceleration valve actuator.

Figure 20. - Schedule of fuel flow as function of compressor pressure rise followed by acceleration control.

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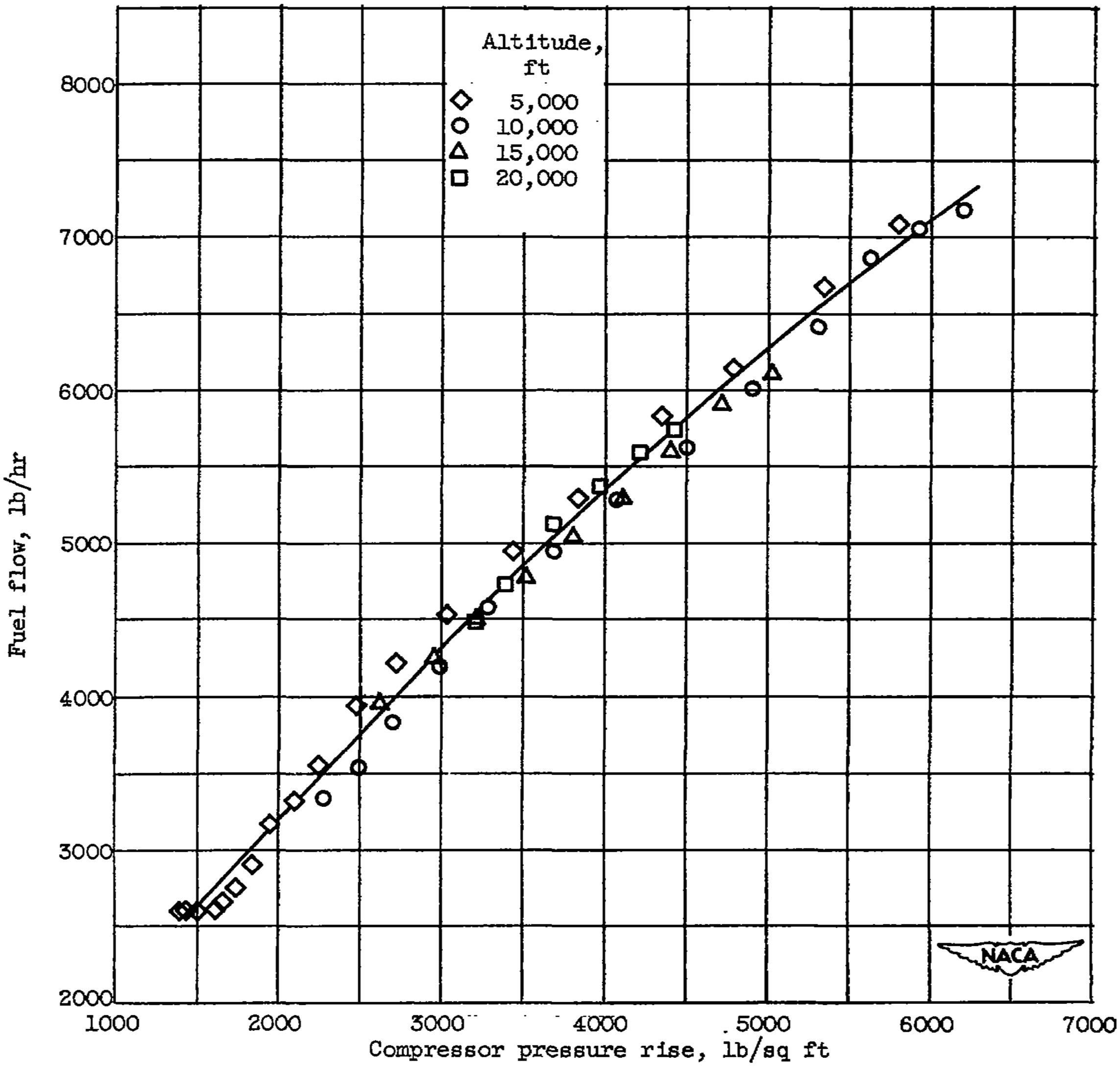
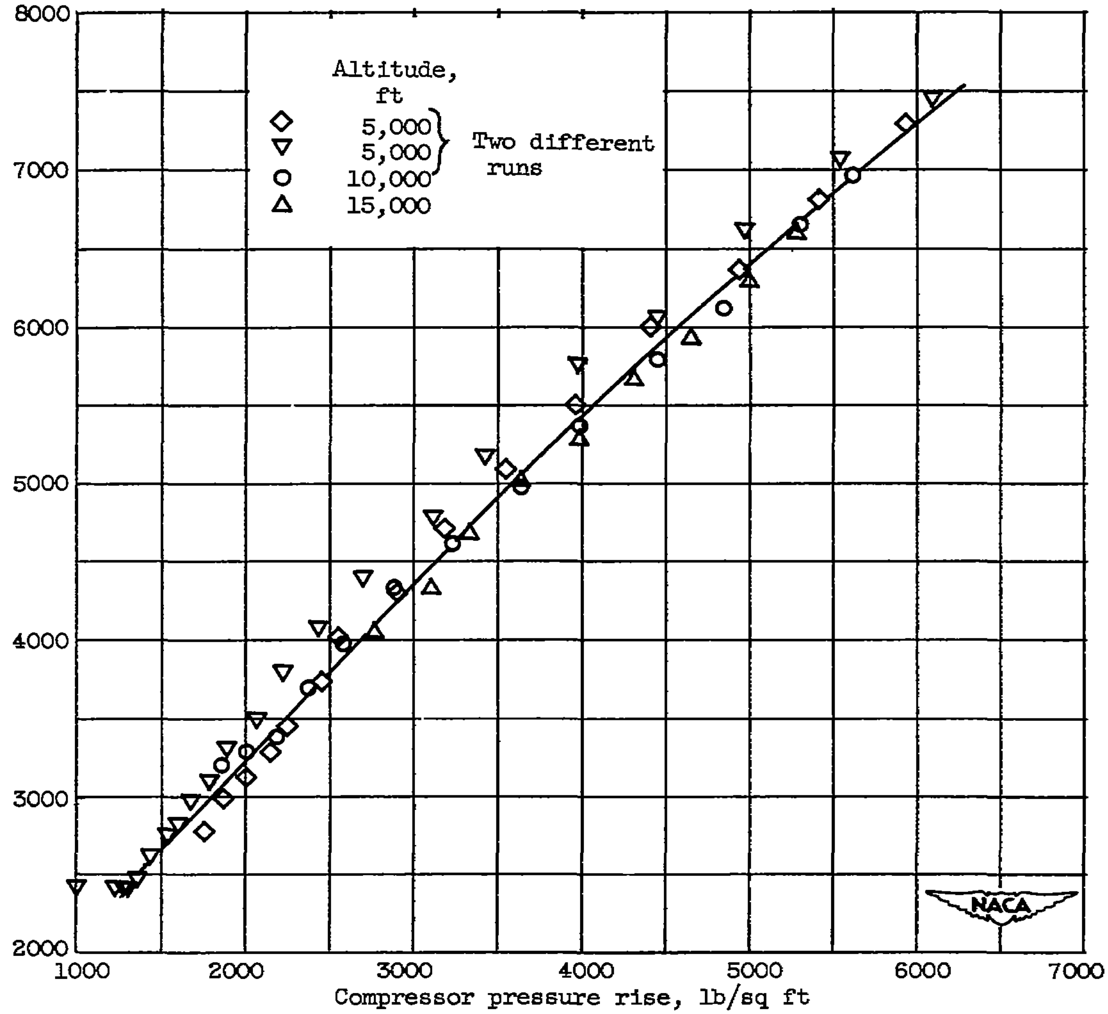


(b) Second setting of acceleration valve actuator.

Figure 20. - Continued. Schedule of fuel flow as function of compressor pressure rise followed by acceleration control.



(c) Third setting of acceleration valve actuator.

Figure 20. - Concluded. Schedule of fuel flow as function of compressor pressure rise followed by acceleration control.

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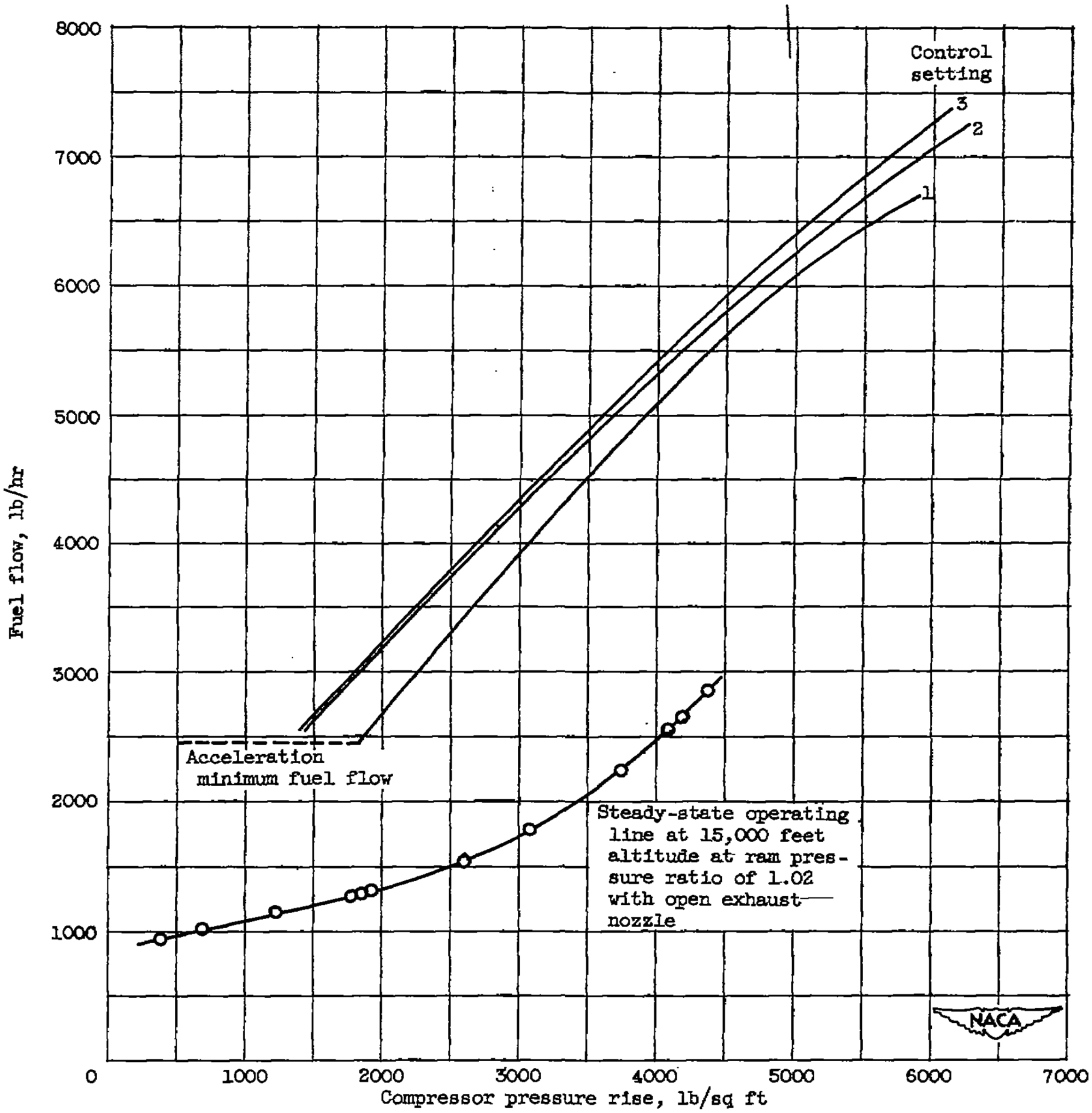

Figure 21. - Comparison of schedules of fuel flow as function of compressor pressure rise for three settings of acceleration valve actuator.

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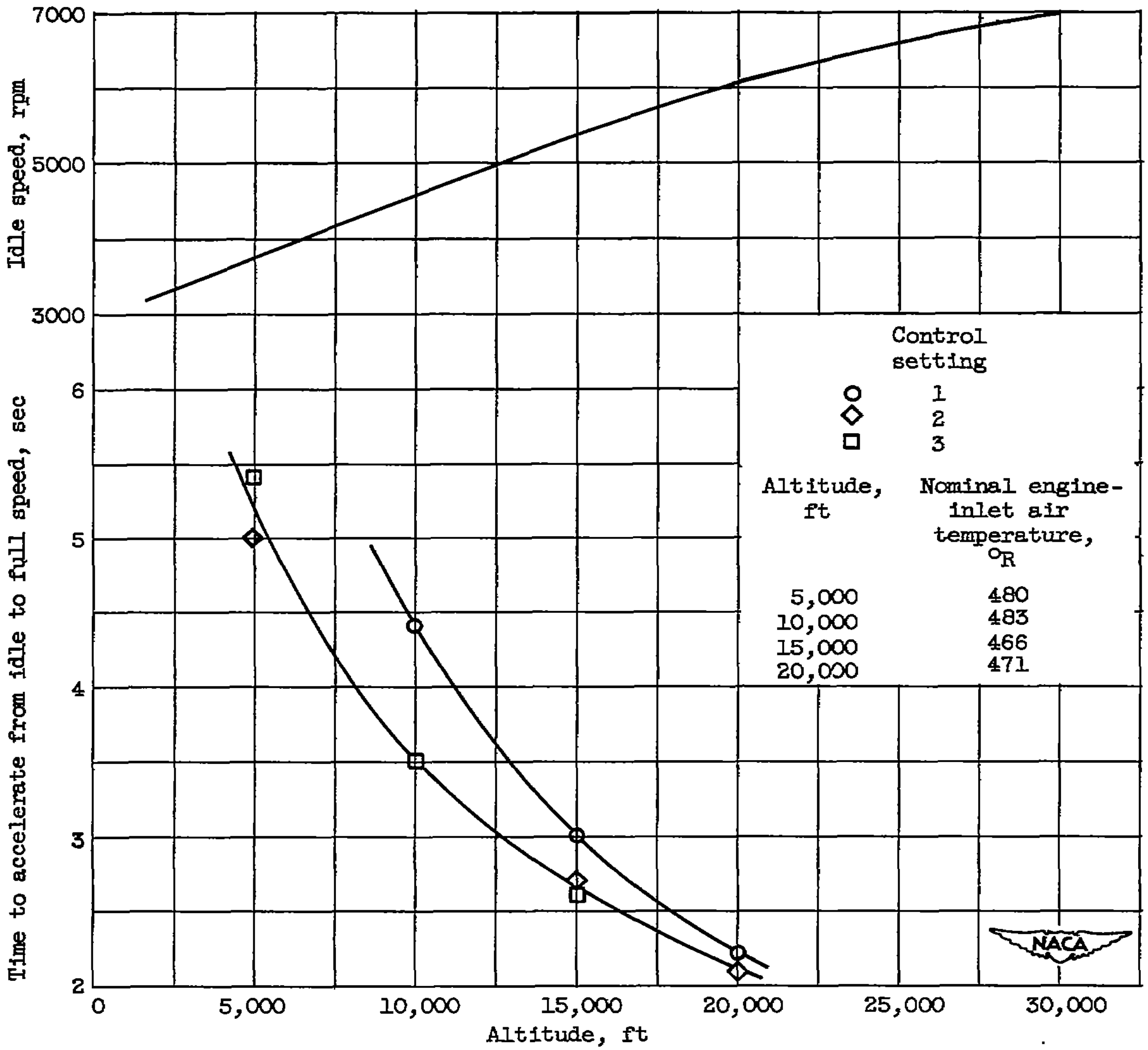

Figure 22. - Variation with altitude of idle speed and of time required for controlled engine to accelerate from idle to full speed for three settings of acceleration valve actuator.

2777

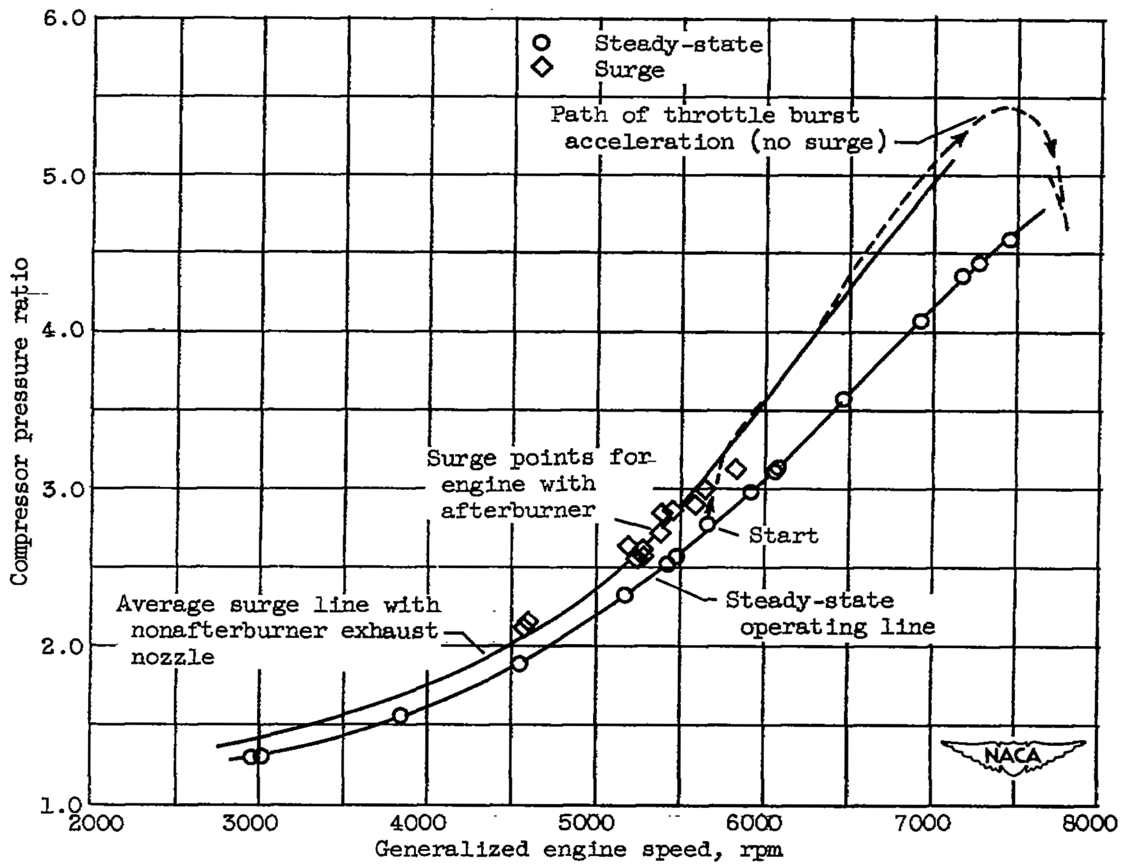

Figure 23. - Comparison of surge line to acceleration path of controlled engine with first setting of acceleration valve actuator on plot of compressor pressure ratio against generalized speed for operation at altitude of 15,000 feet and ram pressure ratio of 1.02.

2777

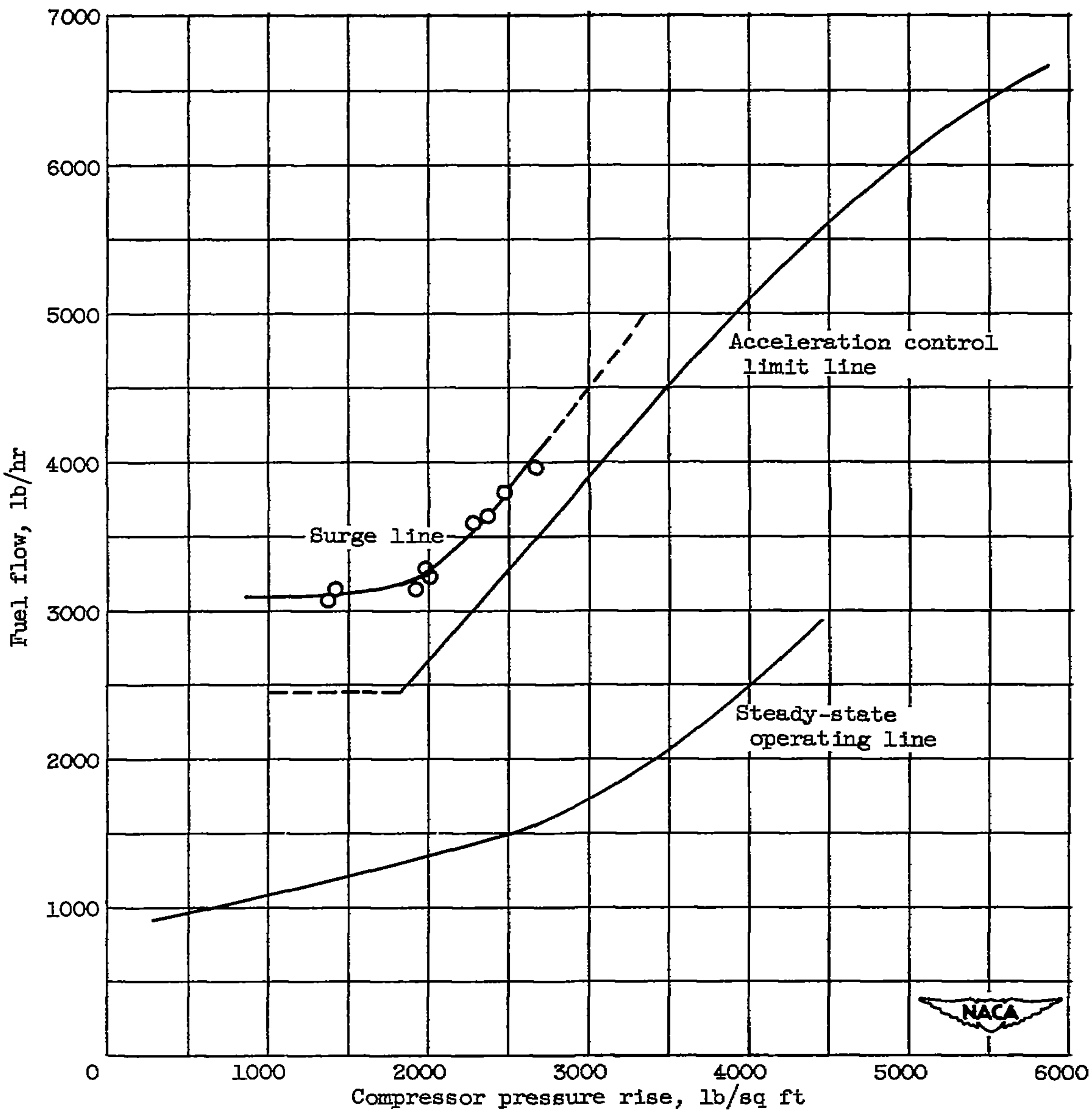

Figure 24. - Comparison of surge line with acceleration control limit line for first setting of acceleration valve actuator on plot of fuel flow against compressor pressure rise for operation at altitude of 15,000 feet and ram pressure ratio of 1.02.

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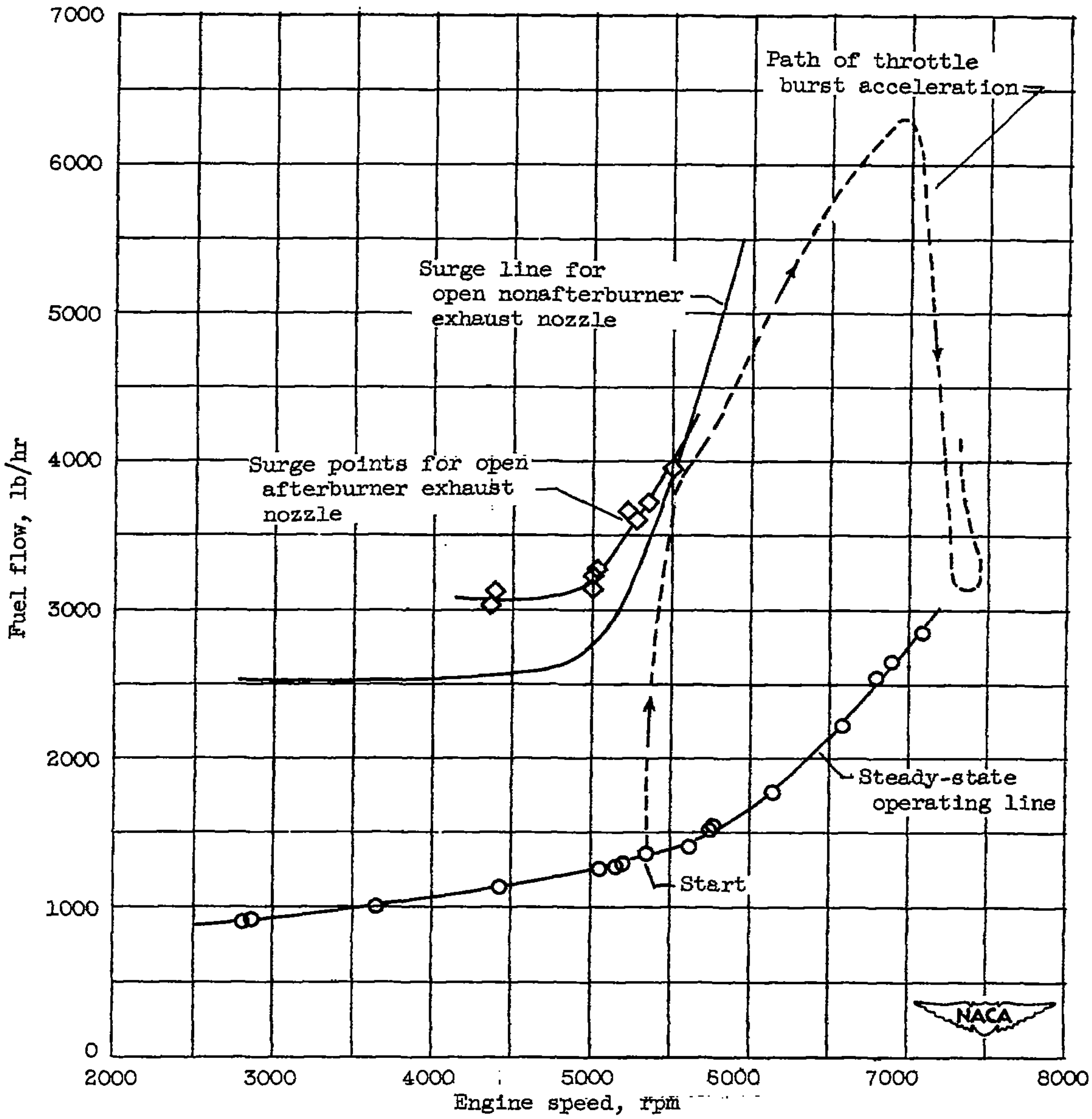

Figure 25. - Comparison of surge line with acceleration path of controlled engine for first setting of acceleration valve actuator on plot of fuel flow against engine speed for operation at altitude of 15,000 feet and ram pressure ratio of 1.02.

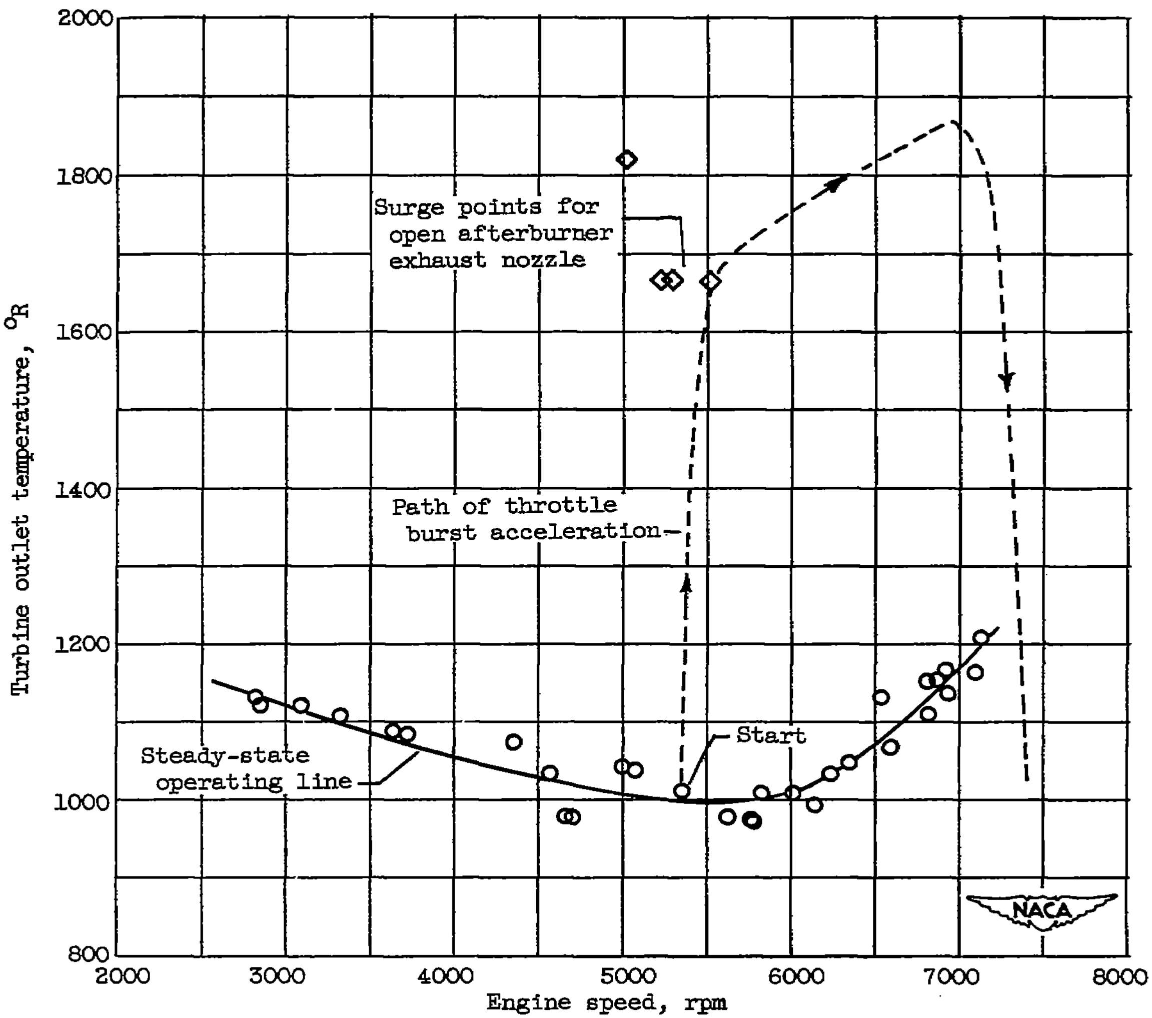

Figure 26. - Comparison of surge points with acceleration path of controlled engine for first setting of acceleration valve actuator on plot of turbine discharge temperature against engine speed for operation at altitude of 15,000 feet and ram pressure ratio of 1.02

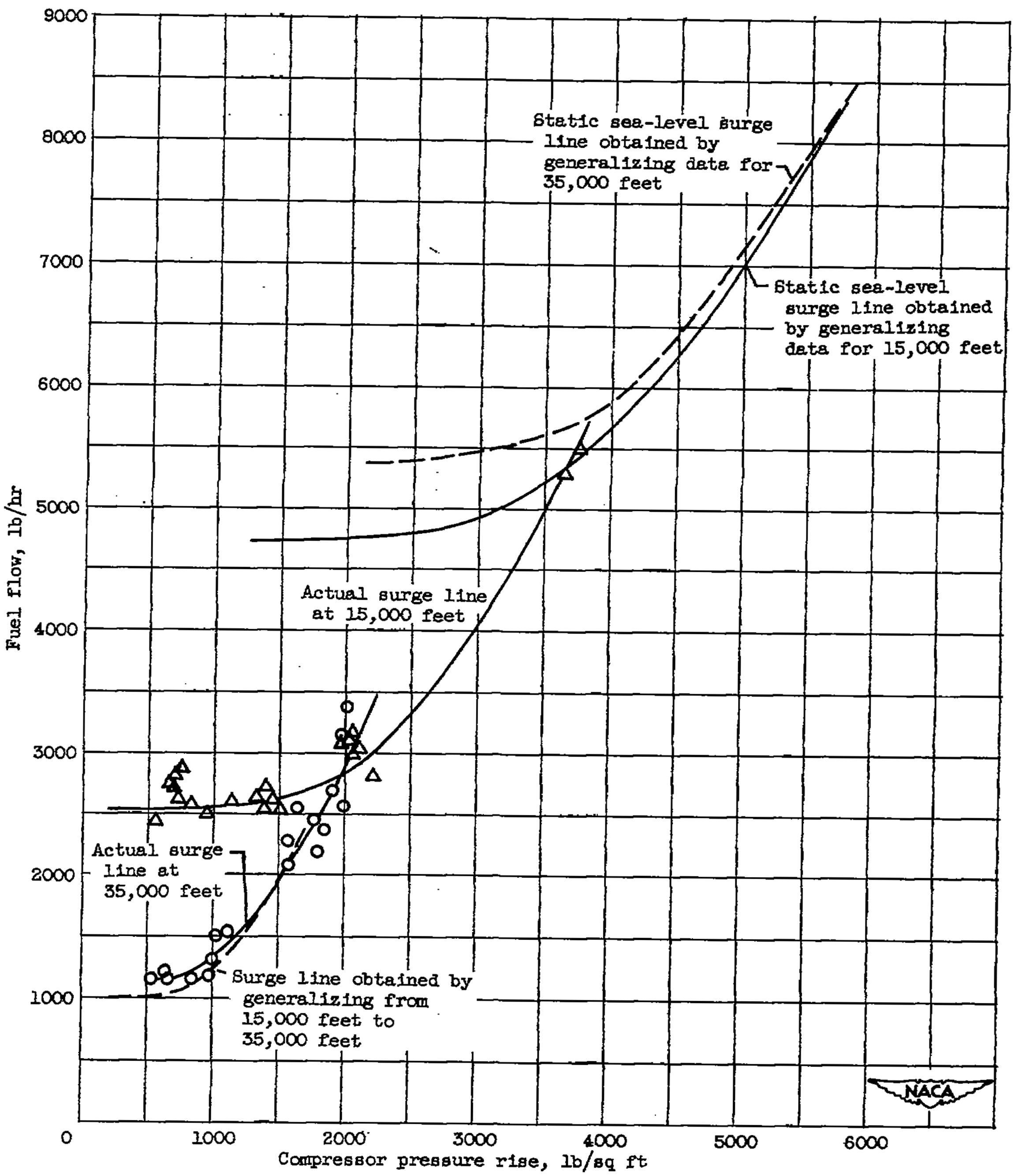

Figure 27. - Surge characteristics for nonafterburning exhaust nozzle.

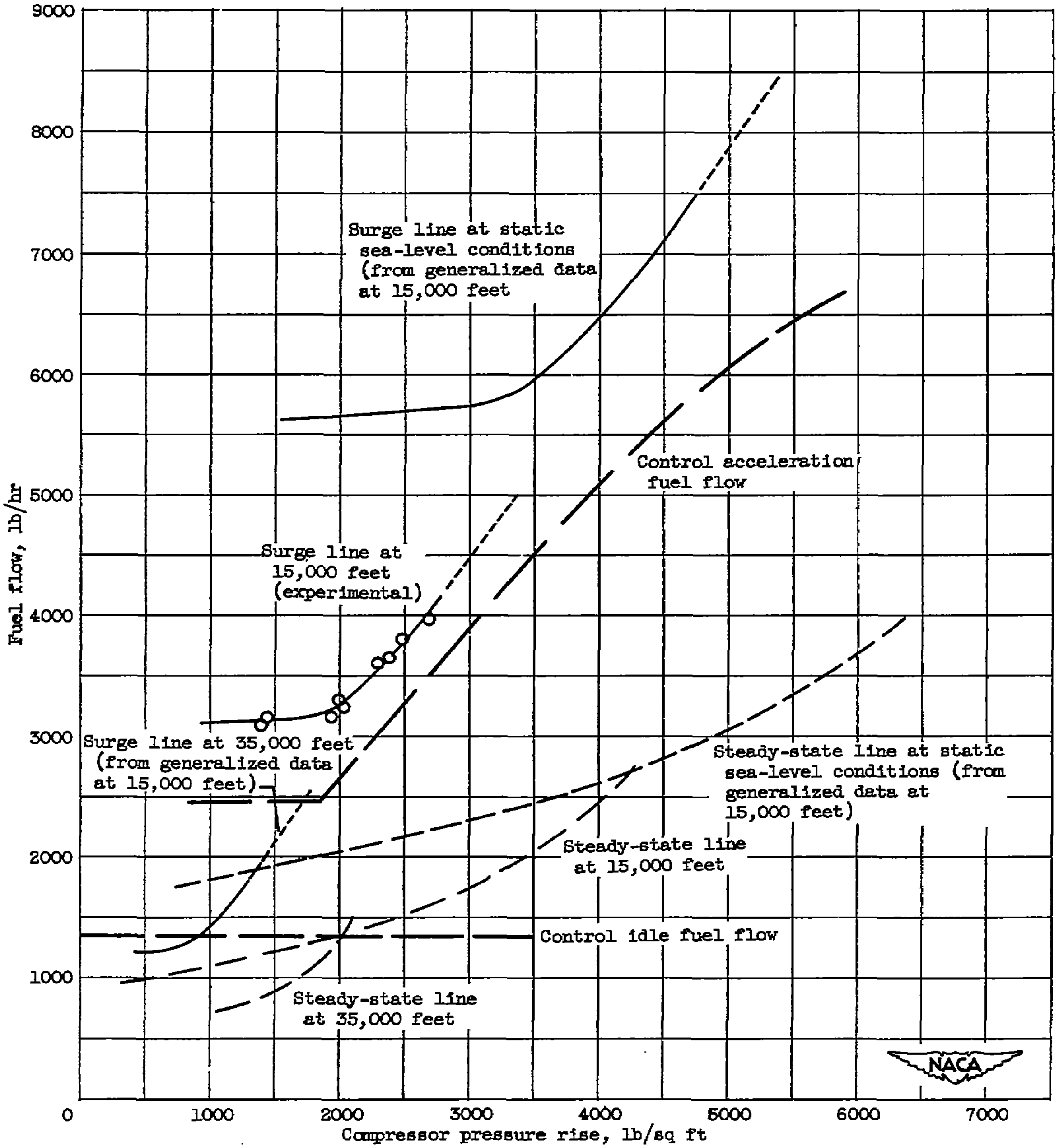

Figure 28. - Comparison of present acceleration fuel flow schedule with engine characteristics for various altitudes.

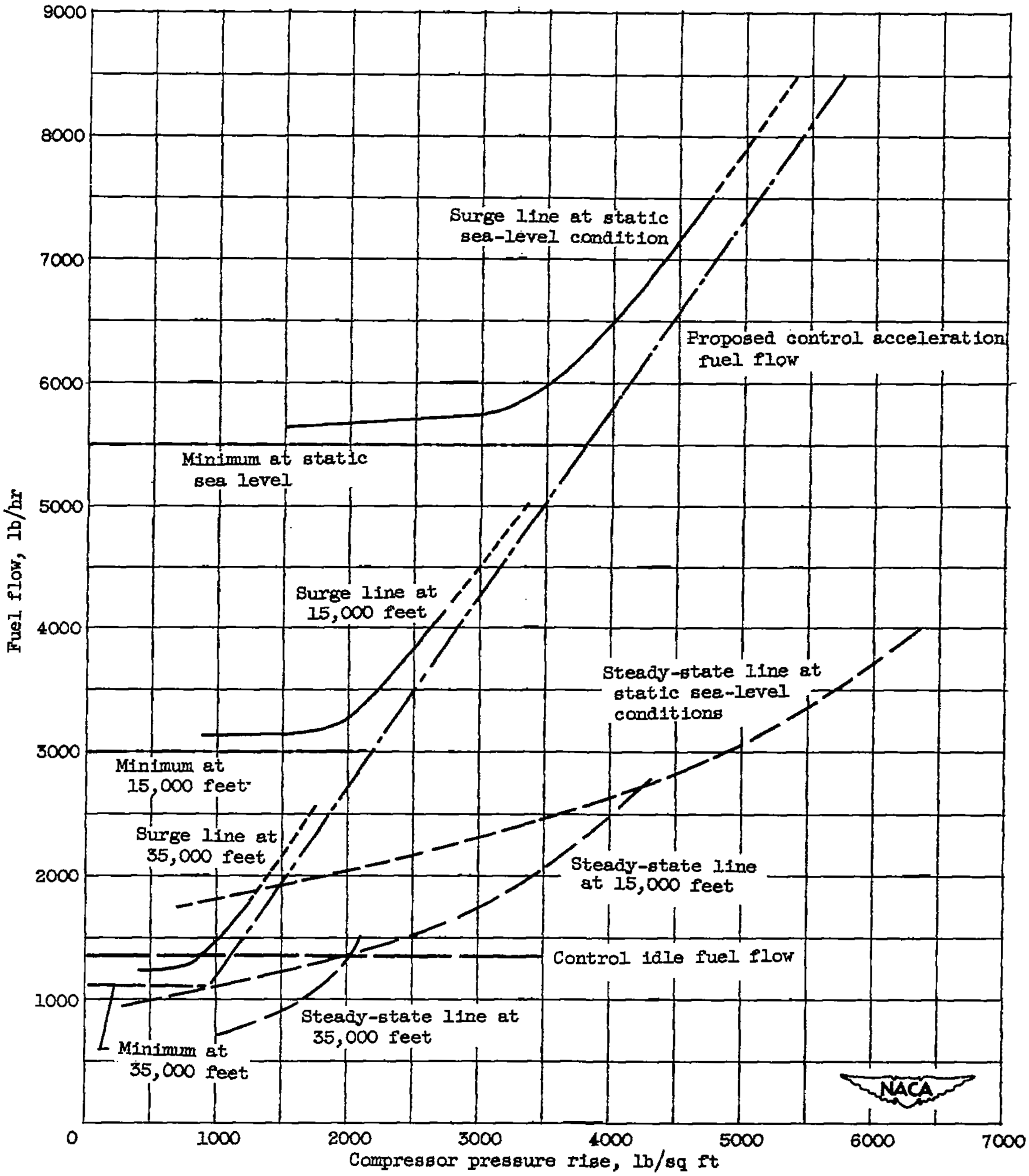

Figure 29. - Comparison of proposed acceleration fuel flow schedule with engine characteristics for various altitudes.

2777

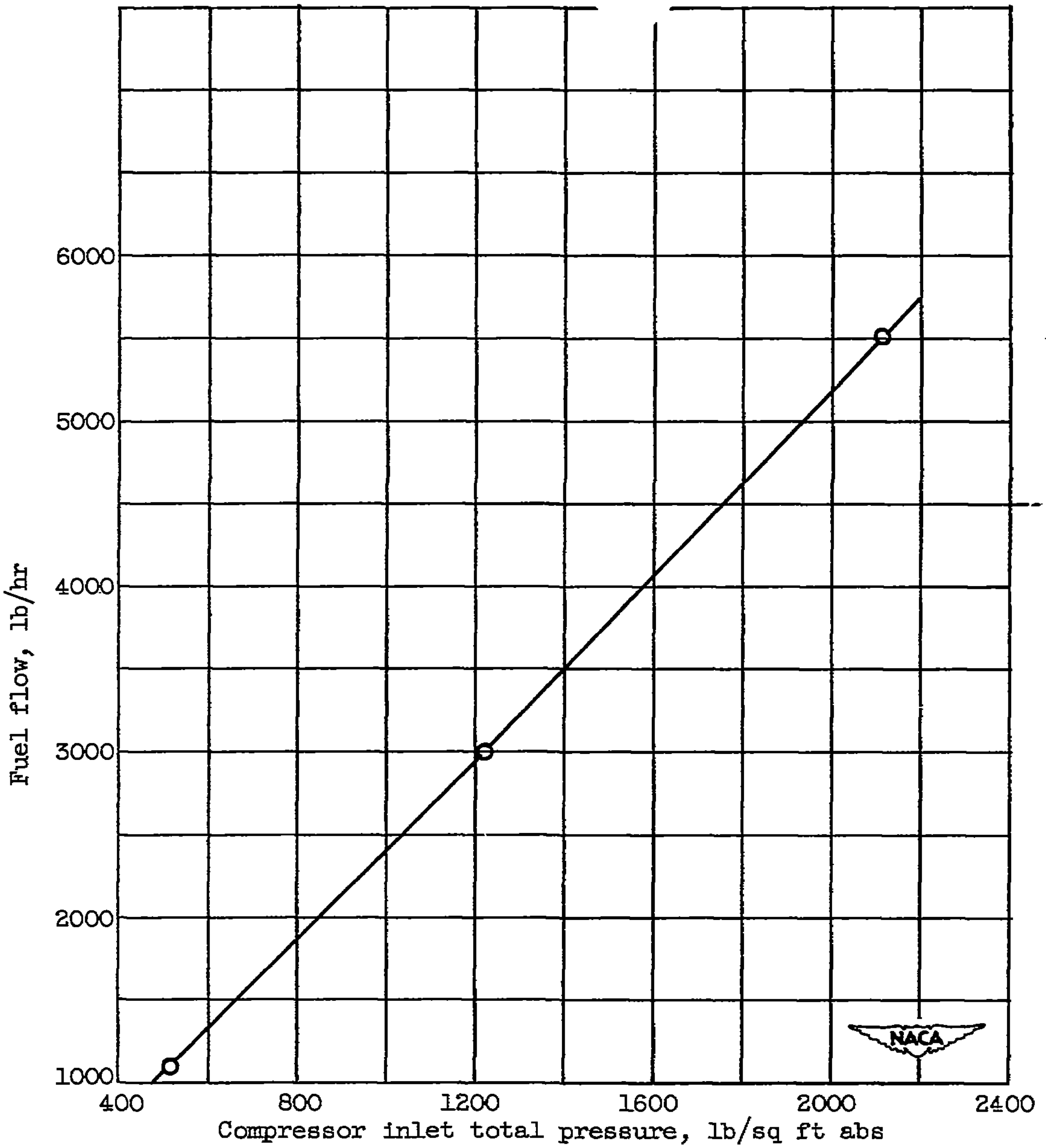

Figure 30. - Variation of acceleration minimum fuel flow with compressor inlet total pressure for proposed modification of fuel schedule.

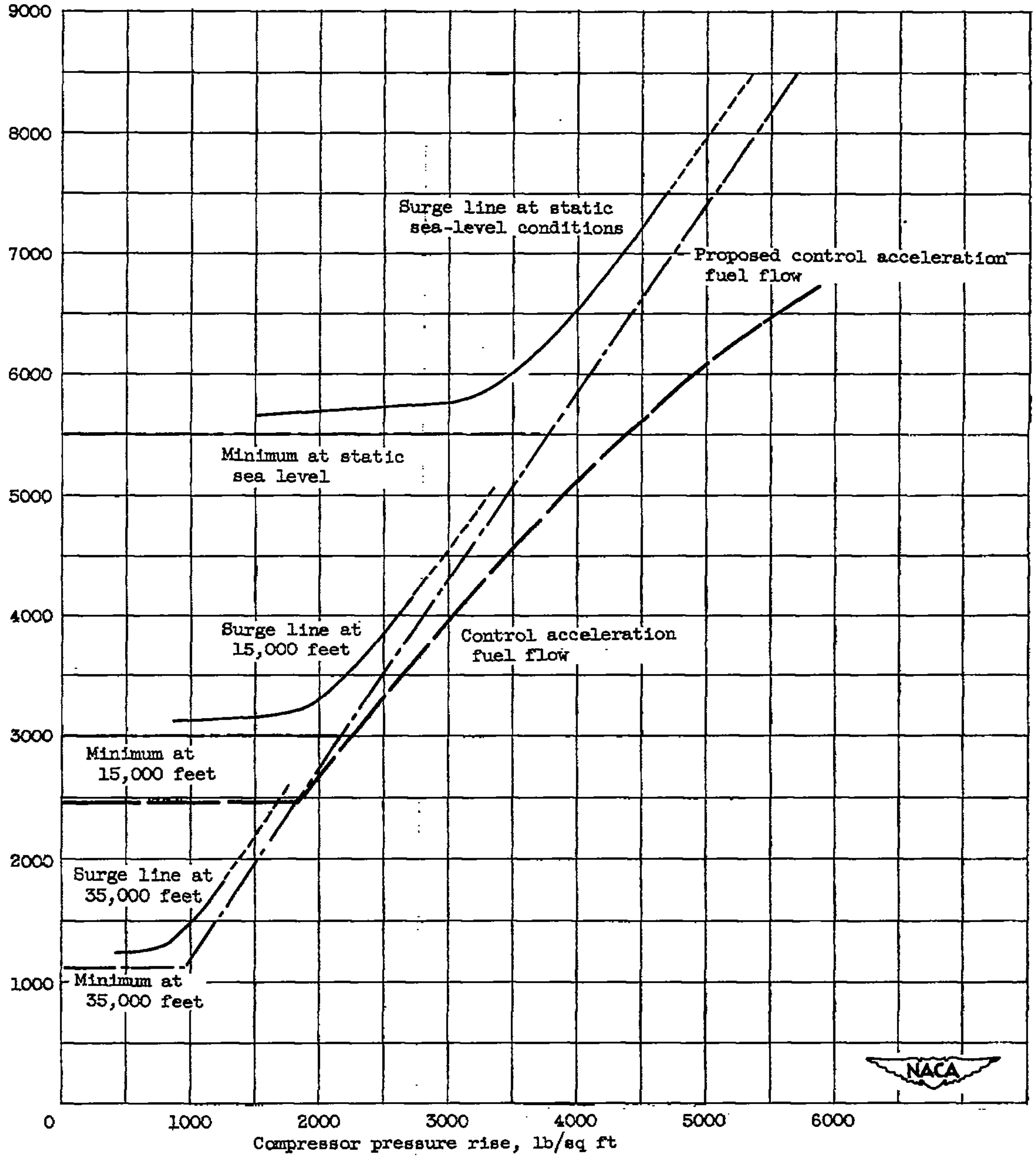

Figure 31. - Comparison of engine characteristics with present and proposed acceleration fuel flow schedules.

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